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EXTENSION OF THE SYTEMATIC APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE EASTERN AND CENTRAL NORTH PACIFIC

by

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December, 1997

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EXTENSION OF THE SYSTEMATIC APPROACH TO TROPICAL CYCLONE TRACK FORECASTING IN THE EASTERN AND CENTRAL NORTH PACIFIC

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of the requirements for the degree of

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ABSTRACT

This study extends an earlier study (White 1995) of the application of the Systematic Approach to tropical cyclone track forecasting of Carr and Elsberry to the eastern and central North Pacific, and contrasts these cases with those in the western North Pacific. The data sample is first expanded to seven years (1990-1996). Modifications to the environment structure conceptual models are: (i) introduction of two Dominant Ridge synoptic regions named Ridge Poleward and Ridge Equatorward based on the bowed orientation of the subtropical anticyclone; and (ii) combining the Weak Westerlies and Accelerating Westerlies into just one synoptic region called Midlatitude Westerlies. Only eight synoptic pattern/region combinations are needed to classify all of the 1858 cases. Additions to the transitional mechanisms include: (i) the formation and dissipation of the mid-level low; (ii) monsoon trough formation; and (iii) orography. A new transition climatology reveals that a large fraction of transitions occur between the regions of the Standard pattern. Subtropical Ridge Modulation and Vertical Wind Shear are determined to be the most important transitional mechanisms. Synoptic analysis sequences are provided to illustrate the synoptic pattern/regions and the primary transitions.

ERRATUM

p.93 **e. S/RE to S/WR to S/MW (Hurricanes Kenneth and Lidia 1993)**

should read

e. S/RP to M/PF to S/WR to S/MW (Hurricanes Kenneth and Lidia 1993)

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The author would like to thank Professors Russell Elsberry and Lester Carr for their guidance, diligence, and extreme patience. Thanks are also in order for my family which has always supported me, my local families of the Drurys, Huddlestons, and Raschs who always make me feel at home, and last but not least, Sam Farina who first enlightened me to the world of meteorology.

I. INTRODUCTION

A. MOTIVATION

The tropical cyclone (TC), which is arguably the most destructive natural phenomenon, occurs over and near every tropical ocean in the world. The United States operates three forecast centers to warn civilian and military customers. The Joint Typhoon Warning Center (JTWC) on Guam is run by the U.S. military to provide forecasts for the western North Pacific, South Pacific, and Indian oceans. The Department of Commerce's National Weather Service has two centers, the National Hurricane Center (NHC) in Miami, which is responsible for the North Atlantic and eastern North Pacific extending as far west as 140°W, as well as the Central Pacific Hurricane Center (CPHC), which is responsible for the North Pacific between the dateline and 140°W.

The sparsity of observations over ocean regions hinders TC motion and structure forecasting at many levels. First, forecasters usually have no hope of having an accurate depiction of the TC structure in real-time, and only have a slightly better picture of the surrounding environment. This slight advantage for the environment has resulted in an environment-centered forecast philosophy that typically does not properly include interaction of the TC with its environment. Although the environmental flow is the primary driving force of the TC motion, a large TC can have a significant effect on the environment and hence modify the actual environmental flow. Second, forecasters are forced to rely on statistical techniques, which usually are lacking in dynamical reasoning, or numerical models that may have deficiencies in real-time data and inherent shortcomings of numerical

methods. Third, the lack of data has, over the years, led to separate studies of track, intensity, and wind distribution, all three of which are actually dependent upon one another. Finally, the absence of a systematic and standardized approach used by the entire forecasting community leads to a degradation of forecast consistency, whether between individual forecasters at the same center or with other forecast centers.

The Systematic and Integrated Approach to Tropical Cyclone (TC) Track Forecasting (hereafter Systematic Approach) of Carr and Elsberry (1994) was originally developed as a framework with which to apply recent research to operational forecasting of western North Pacific (WPac) TCs. The Systematic Approach recognizes and integrates the effects of both the environment and TC by allowing feedback between them. Also, it establishes a common language with which forecasters can better describe forecast scenarios.

One of the objectives of this thesis is to demonstrate that the basic philosophy of the Systematic Approach can also be applied to the eastern and central North Pacific (ECPac) TCs as long as modifications are made to account for the different environmental flows. Hence, this common language can be used by forecasters at more than just one forecast center.

Although the majority of ECPac TC tracks during the 1990-96 seasons (Fig. 1) are westward and away from the North American continent, these storms still have a profound effect on human activity. Hawaii is always a potential target for TCs, and the occasional storm that hits the western coast of Mexico or Central America can lead to disastrous flooding and loss of life. The heavily-travelled shipping lanes along the Central American

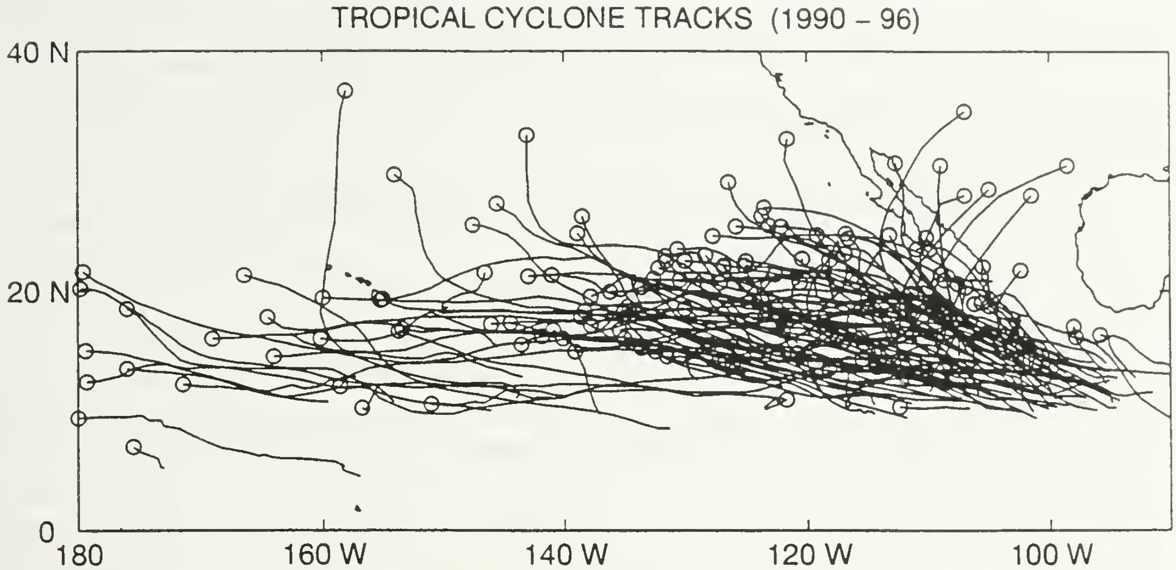


Figure 1. Summary of TC tracks from NHC and CPHC during 1990 - 96. The ending position is indicated with a circle.

coast leading to the Panama Canal can become impassable owing to a TC, and may greatly affect U.S. Navy deployments and other operations in the area.

B. PREVIOUS STUDIES

1. Western North Pacific Systematic Approach knowledge base

Carr and Elsberry (1994) mapped out the fundamental steps that a forecaster should perform when formulating a forecast, and they noted the resources and basic knowledge bases that the forecaster has available (Fig. 2). First, the forecaster must analyze the numerical guidance by examining the numerical model fields and integrating information from hand analyses and satellite imagery into the current description of the atmosphere. Armed with the knowledge and conceptual models of how the atmosphere usually works, and understanding how the numerical model behaves in certain situations, the forecaster can

determine how much to trust the model. The forecaster, therefore, is guided through an examination of the analysis and model prognostic fields to understand what is physically causing the TC motion, as opposed to just accepting a model track forecast at face value.

The Systematic Approach flowchart in Fig. 2 is applicable in any forecast situation, no matter the location or even type of natural phenomenon being forecast. For instance, the same principles should apply when forecasting TC tracks in the ECPac just as they do in WPac. The only caveat is that the TC and environment structure will be different from one section of the world to another. Therefore, the Systematic Approach knowledge base, which

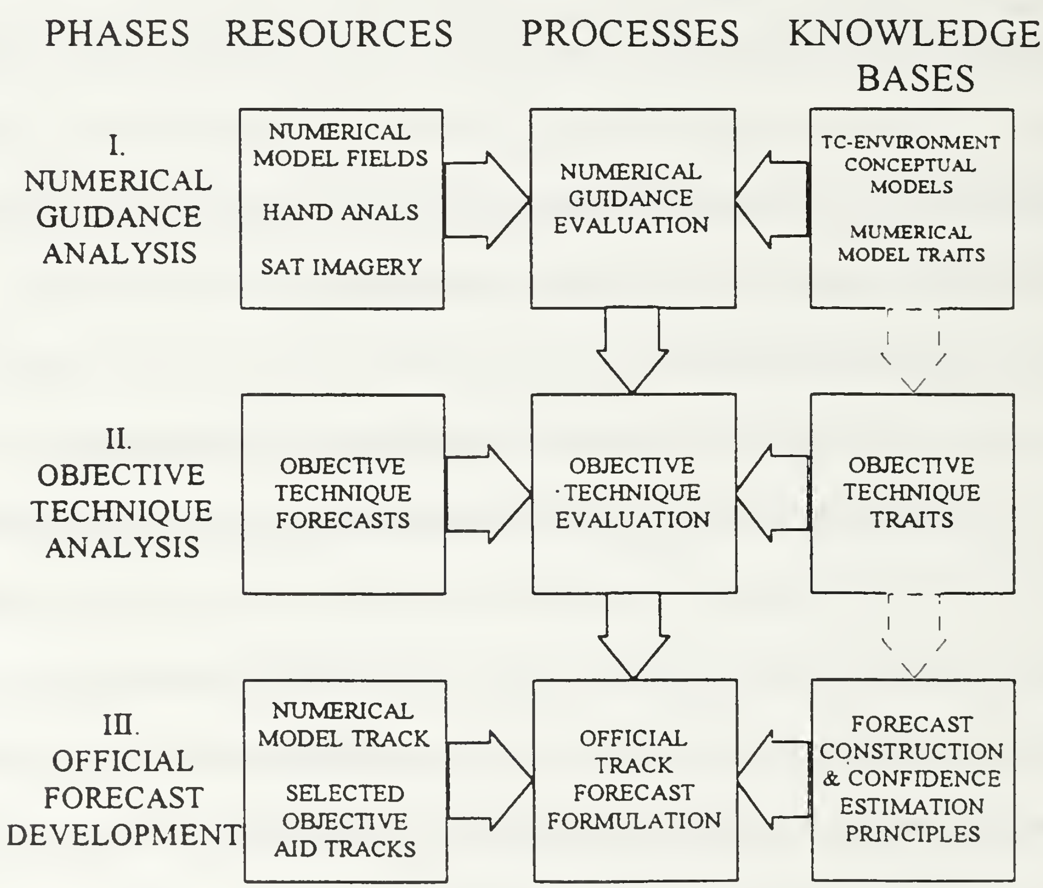


Figure 2. Flow chart of the three phases (left side) and components (top) in the Systematic Approach (from Carr and Elsberry 1994). This study will focus on the first phase only.

includes the TC and environment conceptual models and numerical model traits, must be redefined for the new basin. Of course, a new knowledge base in phase I in Fig. 2 affects the results in the following phases; however, the same procedures are followed as in WPac, the numbers are just different.

This section will briefly introduce the TC and environment conceptual models that comprise the knowledge base initially introduced in the WPac (Fig. 3). An important aspect of the overall Systematic Approach framework is that the TC and environment are not independent. As a matter of fact, either one can affect the other via a number of transitional mechanisms (Fig. 3, bottom), and the result is an effect on the TC track.

a. Environment Structure

Carr and Elsberry (1994) identified four recurring synoptic patterns in the WPac: Standard (S), Poleward (P), Monsoon Gyre (G), and Multiple TC (M) (Fig. 4). These patterns represent the relative orientation of TCs with surrounding anticyclones and other cyclonic circulations at the steering level, which is typically taken to be 500 hPa. Each of these four synoptic patterns is subdivided into two or three smaller synoptic regions that represent different environmental flows and TC tracks. A study of eight WPac TC seasons (1989-96) led to the following results.

The Standard (S) pattern (Fig. 4a), which is the most common synoptic pattern and occurs about 60% of the time, is characterized by a predominantly zonal subtropical anticyclone (STA) with trade wind easterlies (midlatitude westerlies) equatorward (poleward) of its axis. The strength of the STA, which is the driving force of

the trade wind easterlies, led to the naming of the synoptic region equatorward of the STA axis as Dominant Ridge (DR). The TCs in the DR region are often long straight-runners heading toward the west-northwest that account for 52% of all pattern/region classifications. Sometimes, a break forms within the usually strong STA, either by a digging midlatitude trough or by the TC Rossby wave dispersion effect that creates ridge-eroding positive vorticity advection (PVA) in the northwest quadrant of a (Northern Hemisphere) TC. This small synoptic region, which is called the Weakened Ridge (WR) in Fig. 4a, is a col in the STA and thus is characterized by a very slow steering flow. It can be described as a temporary cusp, because a TC usually spends very little time there, and the WR region accounts for only 4% of all classifications. The TC either returns to the DR region, and thus performs a "stair-step" track, or continues into the Midlatitude Westerlies (MW) region poleward of the ridge axis (Fig. 4a). The TCs in the Standard pattern MW region (S/MW) also account for 4% of all classifications, and they are often advected to the northeast quite quickly by the jet stream and undergo extratropical transition or decay. With such a recurvature track, the isotach maximum will rotate from a position poleward of the TC in the DR region, to a eastern position in the WR region, and finally to a southern position in the MW region (Fig. 4a). These isotach maximum positions are consistent with the environmental steering flow changes from westward to northward and then eastward.

The second most common (30%) synoptic pattern of WPac is the Poleward (P), which is characterized by a meridionally-oriented anticyclone (Fig. 4b). The TCs in the Poleward-Oriented (PO) synoptic region (21%) are in a poleward environmental flow to the

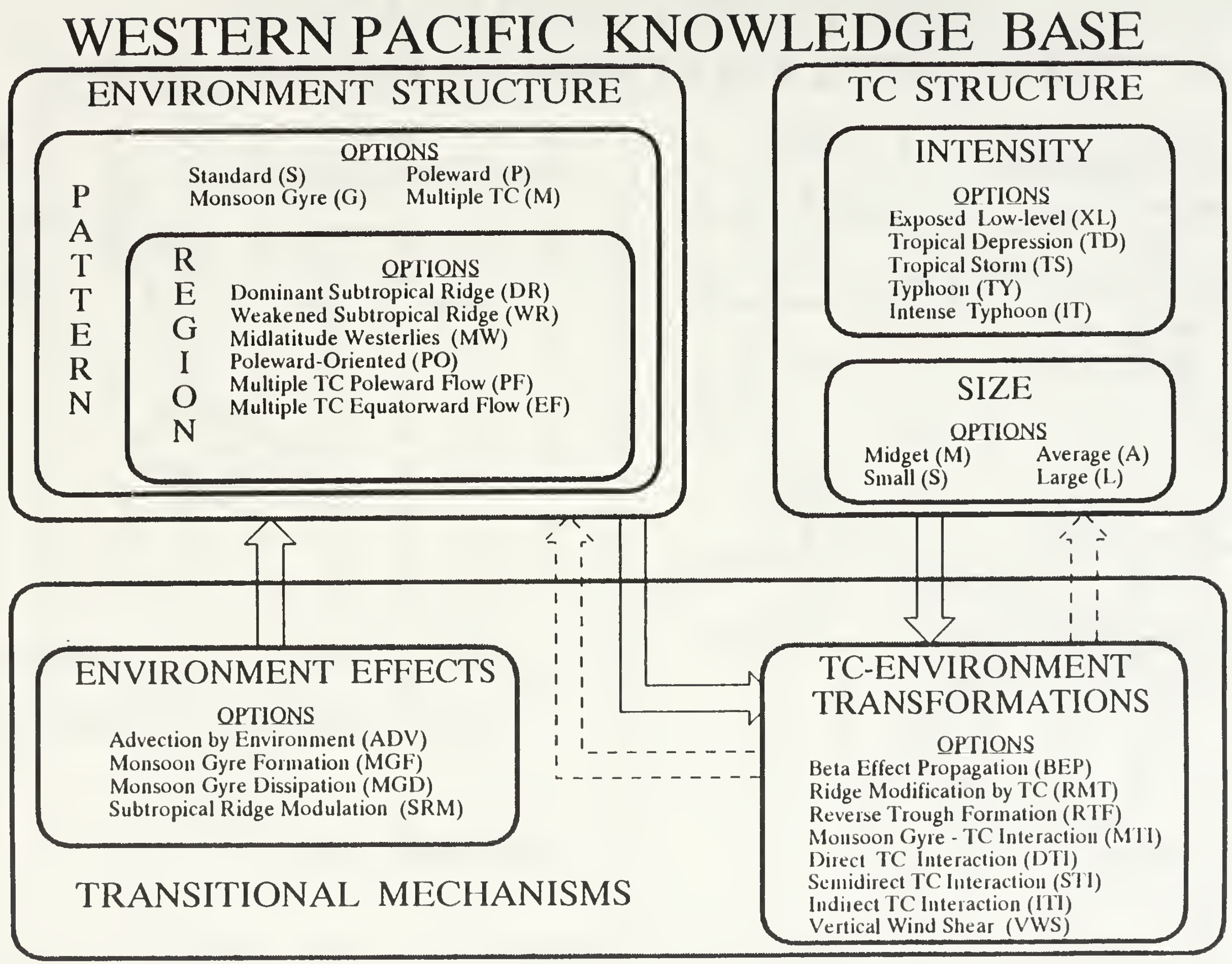


Figure 3. Systematic Approach knowledge base conceptual framework of TC motion effects of Environmental Structure, TC Structure, Transitional Mechanisms, and the interactions between them for the western North Pacific (from Carr and Elsberry 1994).

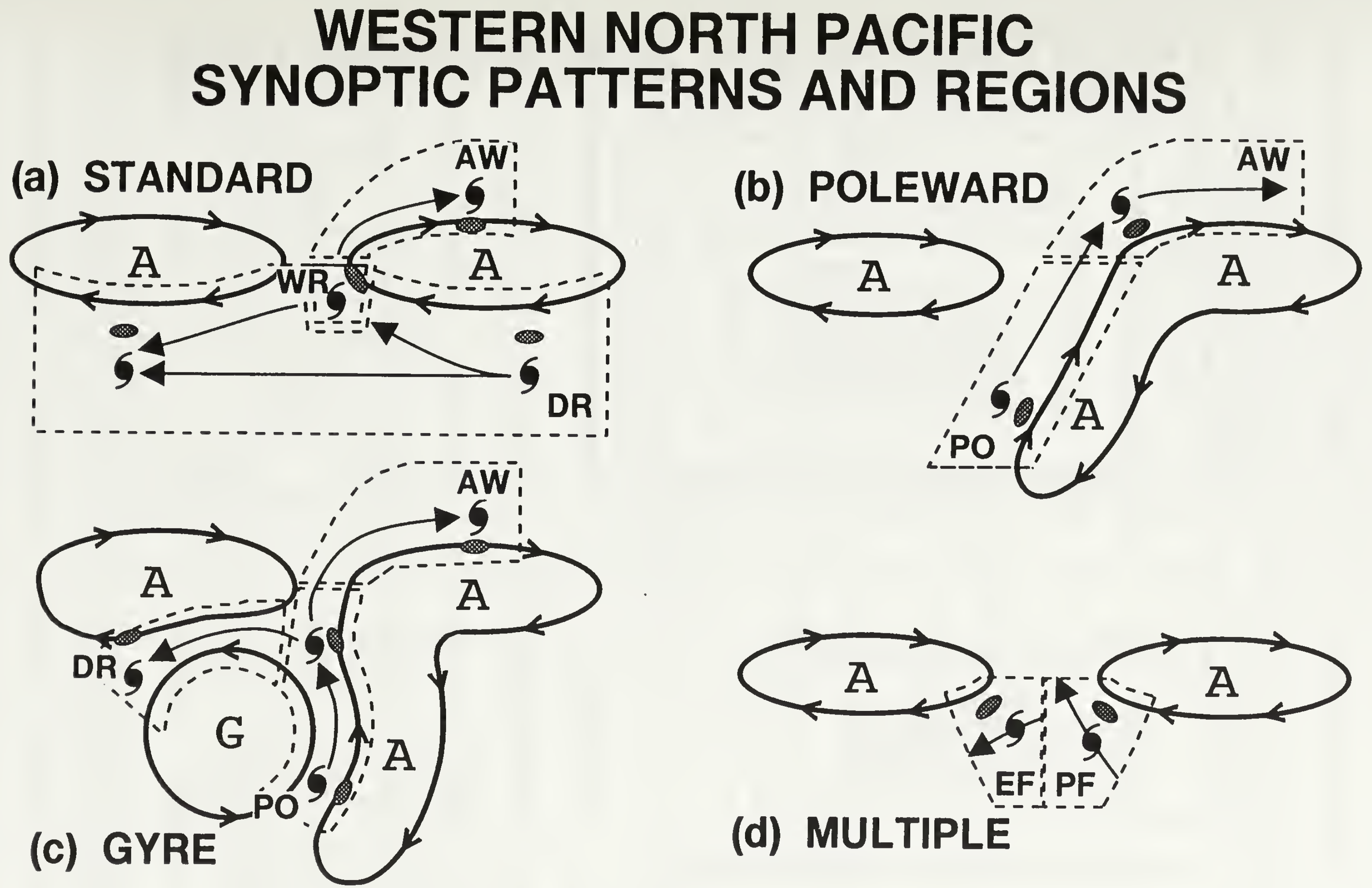


Figure 4. Schematics of the four Synoptic Patterns and Regions of the western North Pacific. Arrows represent typical tracks of TCs that can move between different regions, but within a particular pattern. The shaded elliptic regions relative to the TC positions represent the isotach maximum.

west and northwest of this meridionally-oriented anticyclone. Their tracks are longer than those in S/WR because the P/PO region is larger and the translation speeds are larger because of a stronger environmental flow. If the Poleward pattern persists, the TC may be advected into the MW synoptic region (Fig. 4b). Quite a few TCs eventually complete a transition at some point in their lives to the Poleward Pattern, so many end up moving poleward of the STA axis while in the Poleward Pattern. The result is that more classifications are in P/MW than S/MW (9% as opposed to only 4%). The TCs in both MW regions have similar fast-moving tracks off to the northeast. Notice that the isotach maximum remains on the right side relative to the TC path in the P/PO through P/MW regions in Fig. 4b.

The monsoon Gyre pattern (G) is classified 7% of the time in WPac (Fig. 4c). Lander (1994) describes the monsoon gyre as a large, nearly circular low pressure circulation with a diameter up to 2500 km that occurs only about once a year over the open ocean. However, similar circulations that are not necessarily that large, but still larger than a TC, have been considered gyres in the Systematic Approach. In the WPac, the number of gyres varies significantly from year to year with an average of about three gyres per year recorded in an 8-y sample. These gyres are low-tropospheric circulations and are not intense with surface pressures only about 6 mb less than that of the surrounding environment. Global numerical models do not always analyze these gyre circulations because of a lack of upper-air data. However, visible satellite imagery is the critical tool that shows moderate convection in the center surrounded by a large region of clear skies that has an outer edge

of low-level cumulus bands wrapping around the equatorward and eastern sides. The cyclonic flow on the eastern edge of these circulations, which is called the Poleward-Oriented (G/PO) region (Fig. 4c), is often strong enough to generate and advect TCs in a counterclockwise manner around the gyre center. On the poleward side of the gyre, a bifurcation of tracks occurs. Some TCs continue to be advected around to the northwest quadrant of the gyre and equatorward of the STA such that the TC is in a steering flow much like in the S/DR pattern/region, except with the additional effect of the gyre to the southeast. Hence, this region is called the Dominant Ridge region of the Gyre pattern (G/DR). Other TCs are advected poleward of the STA axis and move into the Midlatitude Westerlies (G/MW) pattern/region (Fig. 4c).

The fourth synoptic pattern in Fig. 4d is the Multiple (M) TC. The essential feature of this pattern is that the environmental flow for a TC is strengthened between the adjacent STA (high pressure) and the low pressure of another nearby TC. The western TC is in the Equatorward Flow (EF) region between the STA to the northwest and another TC to the east through southeast. The equatorward environmental flow plus the beta propagation of the TC toward the northwest results in a track that ranges from southwest to west. The eastern TC is in the Poleward Flow (PF) region between the STA to the northeast and another TC to the southwest through west. Here, the poleward environmental flow and TC beta propagation work in the same direction to result in a fast track toward the northwest. Oftentimes, the eastern TC would be considered a fast recurver as it moves quickly through the STA axis and into the Midlatitude Westerlies (MW) region, which is here considered to

then be in the Standard pattern (S/MW). It should be noted that the orientation of the STA and the other TC is critical in determining if a TC is in the Multiple (M) TC pattern. Usually, TCs are not oriented precisely zonally as depicted in Fig. 4d. It is quite possible that one TC may be in the Multple pattern while the other remains in another pattern. For instance, if the eastern TC approaches the western TC from the southeast instead of due east, then the western TC will be placed into the EF region while the eastern TC is still well south of the PF region. Eventually, the eastern TC may move poleward into the PF region, even after the western TC has moved out of the EF region.

b. Tropical Cyclone Structure

It is well known (Elsberry 1995) that the structure of the TC, described by the intensity, size, and, most importantly for motion, the outer wind strength, is important in determining the beta (β) propagation effect of the TC on its environment. The stronger the outer winds, the greater the β-propagation. The magnitude of β-propagation toward the northwest, which then may be in a direction different from the environmental flow, can be determined by measuring, or at least inferring, the radius of zero cyclonic tangential wind (Carr and Elsberry 1997). Subsequent Rossby wave dispersion is also proportional to storm strength, and the tendency to form a trailing or peripheral anticyclone as in the P/PO pattern/region (Fig. 4b) is greater for larger TCs.

Although the importance of TC structure is one of the key elements in the Systematic Approach knowledge base (Fig. 3, upper right), no quantitative study on TC structure and its relationship with the other elements of environment structure and

transitional mechanisms has been performed for the ECPac. Initial cursory observations from satellite imagery suggest that ECPac TCs do not exhibit as large a range of size and strength as do the WPac TCs, which implies that recognizing the TC structure may not be as important a feature. Hence, TC structure will not be mentioned much in this report.

c. *Transitional Mechanisms*

Properly identifying the current synoptic environment around a TC provides valuable insight into both the current and potential future motion of the TC. In addition, accurate knowledge of the current TC structure is important for knowing how destructive a TC is. Unfortunately, both the environment and TC structures can change during the forecast period via many transitional mechanisms (Fig. 3, bottom), and hence affect the TC track, intensity, and size. The periods during which any one of these three characteristics of a TC undergoes a transition are when forecasts are difficult and large track forecast errors are more likely. Therefore, recognizing the transitional mechanisms is just as important as properly assigning the environment and TC structures.

Four environment effects on the synoptic scale act upon the TC or environment structure (Fig. 3, bottom left). Eight other transitional mechanisms (Fig. 3, bottom right) involve more complicated interactions of the TC with its environment. These mechanisms, which are called TC-environment transformations, are examples of complex dynamical processes in which the TC plays a role in changing its own structure and surrounding environment, and hence affects its intensity, size, and even track. The twelve transitional mechanisms will be briefly explained.

(1) Environment Effects.

ADVECTION (ADV): The most basic conceptual model for TC motion assumes that the TC has no effect on its environment and is simply advected by the steering flow as a "cork in a stream." (Fig. 5) To a first-order approximation, this concept provides a reasonable description of TC motion. Since TCs are being advected by environmental flow all the time, ADV is considered to be a transitional mechanism (Fig. 3, bottom left) when a TC moves from one synoptic region to another region within a persistent pattern while being steered by the environmental flow. Advection is typically the mechanism by which TCs move into the MW regions of the S, P, and G synoptic patterns.

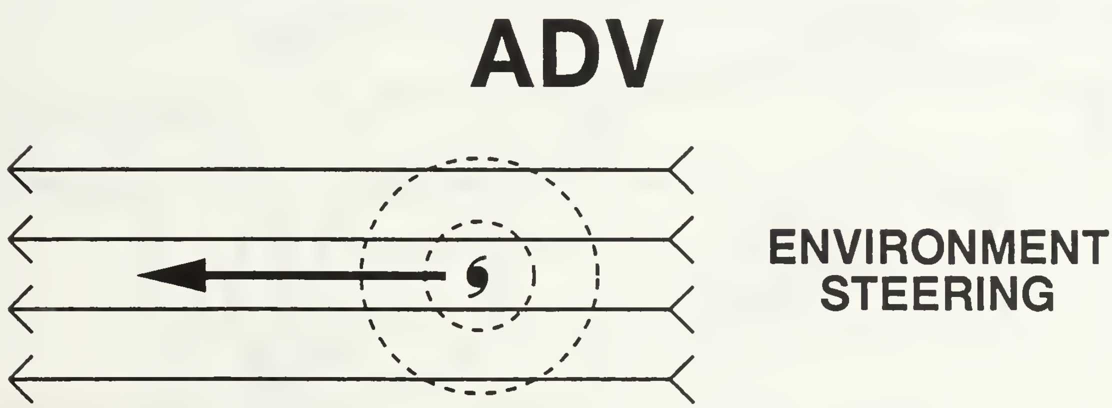


Figure 5. Conceptual model of Advection (ADV). The TC is simply advected along by the environment steering in that same direction.

MONSOON GYRE FORMATION/DISSIPATION (MGF and MGD):

These two environment effects (Fig. 3, bottom left) are noted when a monsoon gyre forms or dissipates near a TC. If a monsoon gyre begins to grow to the west of a TC, the poleward flow on the eastern side of the gyre will increase over the TC (Fig. 6). Eventually, when the gyre is large and strong enough, the TC environment structure is classified as the Poleward-Oriented region in the Gyre pattern. If the strengthening gyre is to the southeast of a TC, then the TC may undergo a transition to Gyre/Dominant Ridge (G/DR). Finally, gyres can dissipate while a TC is still in the PO or DR synoptic region on the gyre periphery. The subsequent pattern/region will then depend on the strength of the peripheral anticyclone as well as possible other nearby TCs.

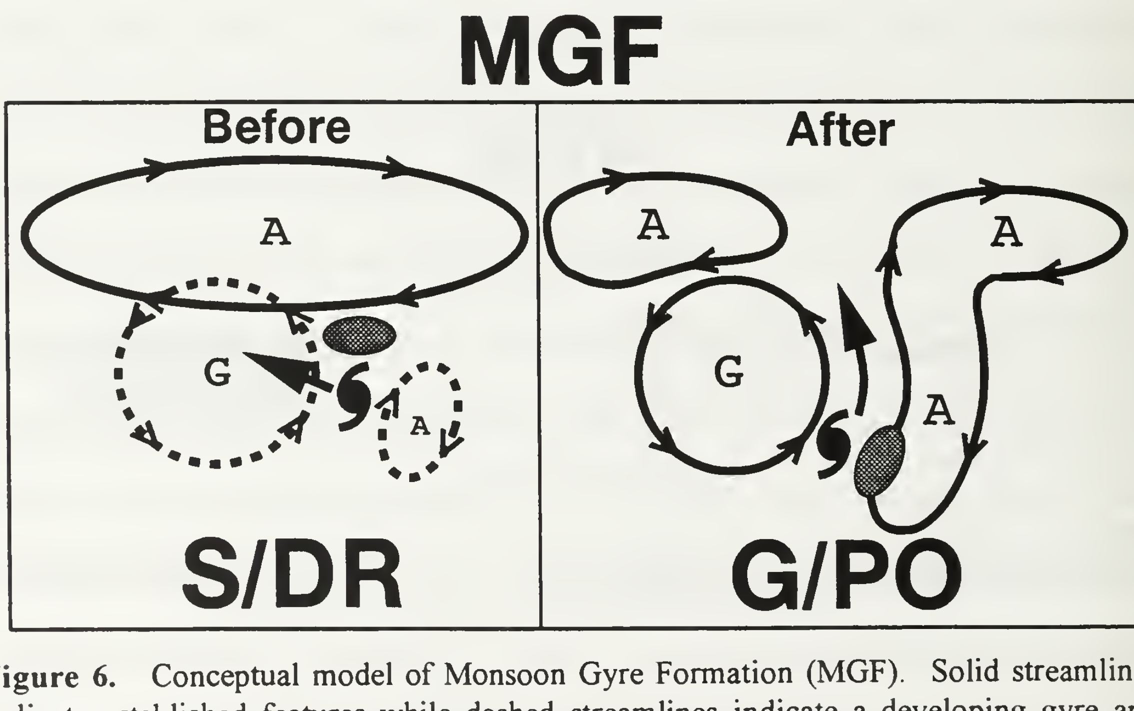


Figure 6. Conceptual model of Monsoon Gyre Formation (MGF). Solid streamlines indicate established features while dashed streamlines indicate a developing gyre and peripheral anticyclone. Arrows indicate TC motion. Shaded elliptic regions relative to the TC positions represent the isotach maximum. The TC typically undergoes a transition from S/DR to G/PO.

SUBTROPICAL RIDGE MODULATION (by a RIDGE or TROUGH) (SRMR/SRMT): As TCs approach the STA axis in any one of the four synoptic patterns in Fig. 4, they come increasingly under the influence of the strong westerlies and midlatitude waves. These waves, or succession of midlatitude ridges and troughs, tend to "ride along" the poleward side of the STA. A passing ridge adds to the STA, and may sometimes become anchored to the STA and establish a high-amplitude midlatitude wave scenario. If a passing ridge happens to be located poleward of a TC moving through a break in the STA, this ridge may impede the TC poleward motion and perhaps even turn the TC to the west. As the TC is then equatorward of the STA and is in strong trade wind easterlies, the motion is again westward. Such a "stair-step" track in association with the SRMR transformation is illustrated by the S/WR to S/DR track in Fig. 4a.

The SRMT transformation is noted when the STA is broken by a passing midlatitude trough. The TC is usually near enough to the new break to begin moving poleward and a recurvature into the S/MW pattern/region (Fig. 4a).

(2) TC-Environment Transformations.

BETA-EFFECT PROPAGATION (BEP): Although the Coriolis parameter (f) varies sinusoidally with latitude, it can be adequately approximated for small meridional displacements by a linear variation in β. For a symmetric TC circulation on a β-plane with no mean flow, this linear effect distorts the initially concentric relative vorticity field into a field of positive (negative) tendencies to the west (east) of the center. In the absence of nonlinear advection, the TC center propagates to the west, i.e., it moves toward

increasing relative vorticity. However, the nonlinear advection effect associated with the symmetric flow around the TC center advects these areas of positive and negative relative vorticity tendencies cyclonically by about 45°, so that the rotated anticyclone (cyclone) is located northeast (southwest) of the TC center. Since the resulting southeasterly flow between these "β-gyres" is on the same scale as the entire TC circulation, this "propagation vector" acts uniformly over the entire TC and advects the TC toward the northwest. This beta-effect propagation (BEP) acts in addition to the environmental steering flow (Fig. 7). Although BEP is always occurring, it is dependent upon the TC size or outer wind strength. A larger TC establishes stronger β-gyres, which advect the TC more poleward and westward than smaller TCs. BEP is usually the transitional mechanism that is involved when the TC is being advected northwestward into the STA axis, i.e., during a transition from S/DR to S/WR.

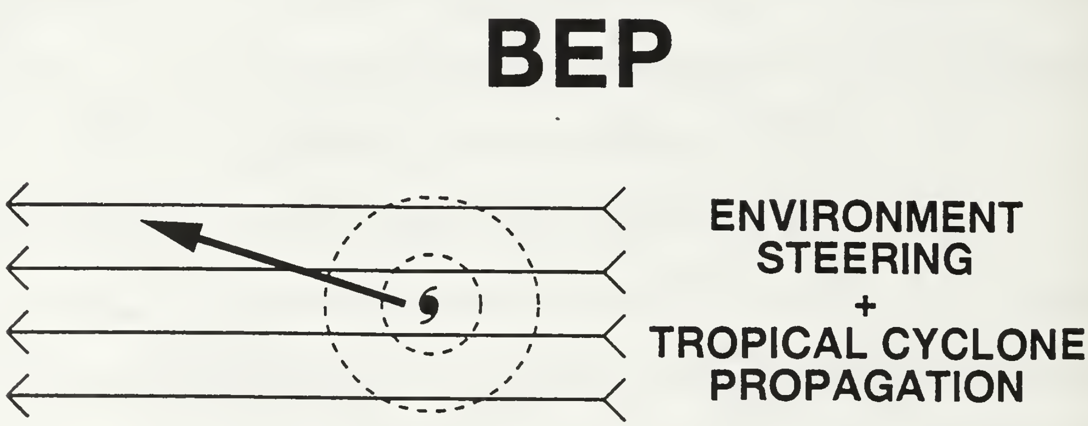


Figure 7. Conceptual model of Beta-Effect Propagation (BEP). In this case, the TC propagates toward the northwest within a background flow of easterlies.

RIDGE MODIFICATION BY A TC (RMT): As soon as β-gyres are established, the TC will move, or propagate, relative to the environmental steering. In addition, Rossby wave dispersion will leave an anticyclone to the southeast in the TC wake (Fig. 8). If a TC has a strong outer wind circulation, then the peripheral anticyclone to the southeast will grow large and strong. If the peripheral anticyclone grows large enough to produce predominantly poleward steering at the location of the TC, then the synoptic environment is considered to be the Poleward synoptic pattern (Fig. 4b), and the TC is typically in the Poleward-Oriented synoptic region. In this sequence, a TC experiences the RMT transformation (Fig. 3, bottom right) and undergoes an environment structure transition from S/DR to P/PO. Although the TC is moving poleward, it is still deep in the tropics and may continue to intensify over high SSTs and in low vertical shear. This scenario of a poleward turn while the TC is still well south of the STA axis may catch a forecaster by surprise if he/she is not watching for a growing peripheral anticyclone to the southeast of the TC in the Northern Hemisphere.

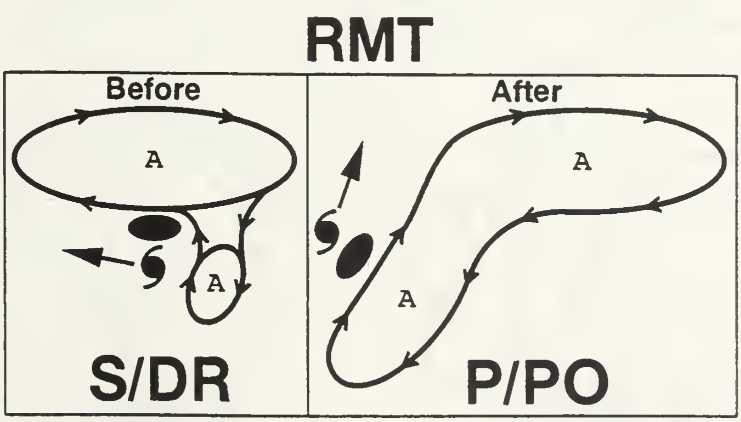


Figure 8. Conceptual model of Ridge Modification by a TC (RMT). A small peripheral anticyclone southeast of the TC grows, attaches to the STA, and modifies the STA. The TC typically undergoes a transition from S/DR to P/PO.

REVERSE TROUGH FORMATION (RTF): In WPac the peak typhoon season is strongly controlled by the monsoon trough, which is climatologically oriented northwest-southeast from southern China to over the Philippines and out toward the Caroline Islands. If two or more TCs in the monsoon trough are oriented properly (slightly southwest-northeast), their separate β-induced peripheral anticyclones can build constructively to the southeast of each TC (Fig. 9). If the eastern TC translates poleward more rapidly, the trough may then become oriented southwest-northeast, which Lander (1996) refers to as a "reverse-oriented" monsoon trough. The result is a large Poleward pattern (Fig. 4b) with two or more TCs creating a reverse-oriented (southwest-northeast) monsoon trough just north of a large peripheral anticyclone. Interestingly, the peripheral anticyclone seems to strengthen uniformly all along its axis. Hence, all of the TCs tend to move poleward within 24 h of each other. The TCs often start the RTF transformation while in S/DR or, if more than one storm is involved, in the M/EF or M/PF pattern/regions.

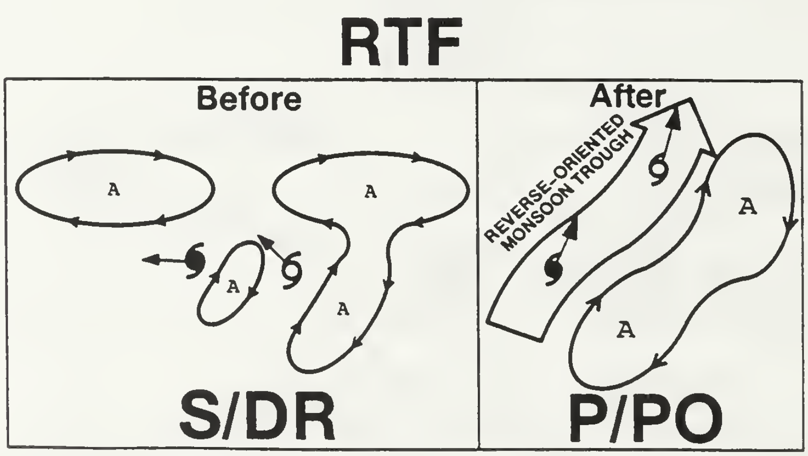


Figure 9. Conceptual model of Reverse Trough Formation (RTF). The peripheral anticyclones of more than one TC grow together, with the eastern anticyclone usually more dominant. The TCs typically undergo a transition from S/DR to P/PO within 24h of each other.

MONSOON GYRE - TC INTERACTION (MTI): Although different in structure, a monsoon gyre and a TC on its periphery are both cyclonic circulations, and they can interact in a way other than just simple advection of the TC by the larger gyre (Fig. 10). In the MTI process, the two separate circulations actually merge to become one large TC. During the merger process, the TC track is usually looping and very difficult to predict(Carr and Elsberry 1995). Meanwhile, a strong peripheral anticyclone is generated to the southeast, and the merged large TC typically moves poleward in the Poleward/Poleward-Oriented pattern/region (Fig. 4b).

DIRECT TC INTERACTION (DTI): The DTI (Fig. 11a) is one of three modes of interactions between two TCs discussed by Carr *et al.* (1997). The interaction is considered "direct" because the circulations of the two TCs actually overlap. This makes DTI analogous to the frequently described Fujiwhara effect in which the primary

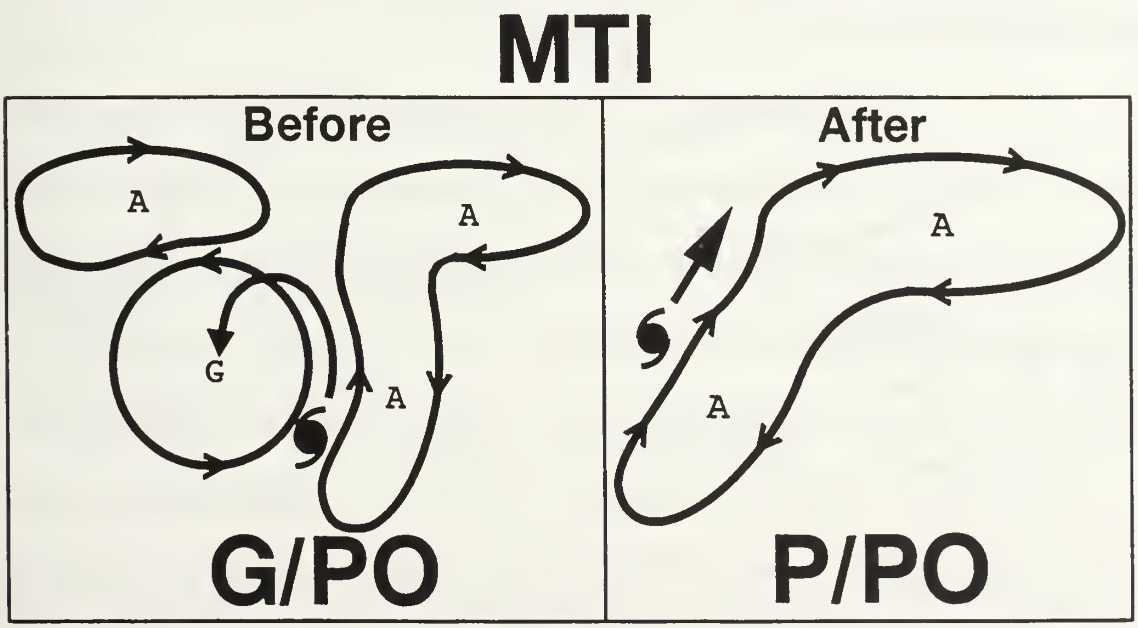


Figure 10. Conceptual model of Monsoon gyre-TC Interaction (MTI). A TC and gyre merge to form one large TC with a large peripheral anticyclone. The TC typically undergoes a transition from G/PO to P/PO with a looping track.

environment steering for one TC is the circulation of an adjacent TC. Since the TC circulations are overlapping in DTI, it only occurs when the TCs are close to each other, with a separation distance less than 10° latitude. In addition to the separation distance, the tracks of the two TCs are highly dependent upon the size and strength of both TCs; hence, the three types of DTI in Fig. 11a describe different scenarios. The DTI1 is a one-way interaction in which a smaller TC is embedded in, and moves cyclonically around, a larger TC circulation. This small TC has a larger cyclonic rotation rate relative to the large TC, but the large TC is deflected very little, if at all. At times, the small TC is sheared apart by the large TC and dissipates. The DTI2 is a two-way interaction in which the two TCs are more similar in size, and both TC centers are within and advected by the circulation of the other TC. Once again, the smaller TC may tend to dissipate. Finally, DTIM is the rare process in which two equally-sized TCs are able to maintain their TC structure while actually merging into one TC.

SEMIDIRECT TC INTERACTION (STI): When the separation distance for two TC centers is between 10° and 20° latitude (Fig. 11b), their circulations usually do not overlap, and there is insufficient space for an anticyclone to be present between them. This scenario is the M pattern in Fig. 4d. The eastern TC in the PF region is said to be undergoing STIE and the western TC in the EF region is undergoing STIW.

INDIRECT TC INTERACTION (ITI): A key feature of the ITI (Fig. 11c) is a larger separation distance (15°-30°) so that an anticyclone exists between the two TCs. The origin of this anticyclone is from the Rossby wave dispersion associated with a

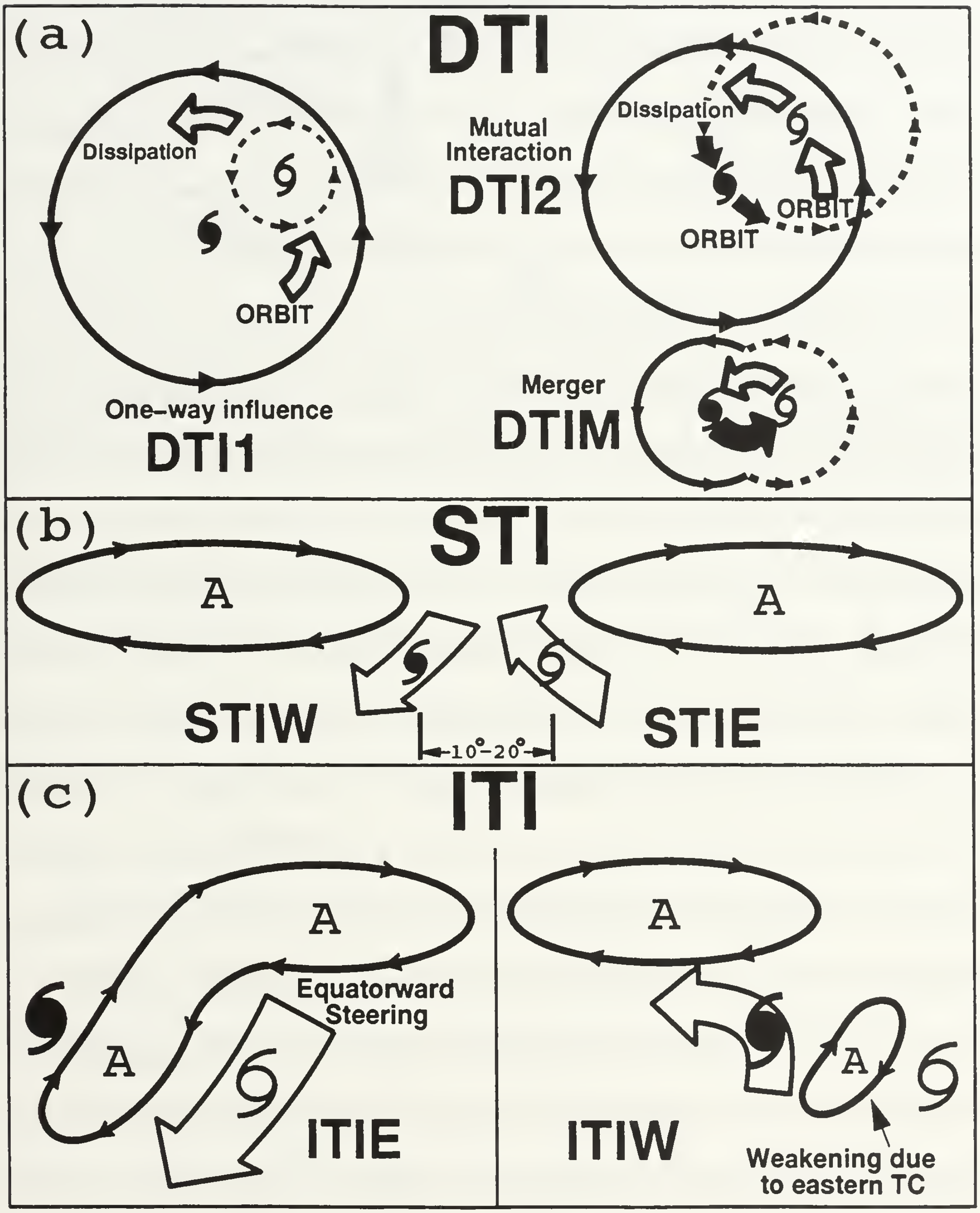


Figure 11. Conceptual models of TC Interactions. (a) Three types of Direct TC Interactions (DTI) exist owing to the difference in relative sizes of the TCs. (b) Semi-direct TC Interactions (STI) involve a Western (Eastern) TC undergoing STIW (STIE), but not necessarily simultaneously. (c) Two types of Indirect TC Interactions can occur depending upon the size and strength of the TCs.

relatively large western TC. Development of this peripheral anticyclone results in a poleward steering flow across the western TC (see Carr and Elsberry 1995, 1997). As the eastern TC approaches the peripheral anticyclone of the western TC, one of two scenarios could occur. First, the peripheral anticyclone may remain strong and an equatorward steering current will be imposed on the eastern TC, which will deflect it to an unusual south of west track (Fig. 11c, left). Because the track of the eastern TC is affected, this transitional mechanism is called ITIE. Notice that a poleward motion (equatorward deflection) of the western (eastern) TC by the intervening peripheral anticyclone will cause an anticyclonic rotation about the centroid between the two TCs. This anticyclonic rotation distinguishes the ITIE from the DTI and STI, both of which have a cyclonic rotation rate. The second scenario occurs if the ridge-eroding PVA ahead of the eastern TC is strong enough to weaken the western TC's peripheral anticyclone (Fig. 11c, right). The western TC's poleward motion decreases, sometimes enough to cause the western TC to turn back to a westward track. This indirect interaction, which is called ITIW, primarily affects the western TC. During ITIW, the rotation about the centroid of the two TCs is either less anticyclonic or even cyclonic, so the rotation rate is not as useful a tool as for ITIE.

VERTICAL WIND SHEAR (VWS): A TC can be ripped apart by vertical wind shear via many processes. Because the primary focus of the Systematic Approach thus far is track forecasting, VWS was specifically introduced as a transitional mechanism in WPac to describe sudden track changes by off-season TCs (Fig. 12). Although not as common as summer TCs, winter TCs do occur in WPac. As they approach

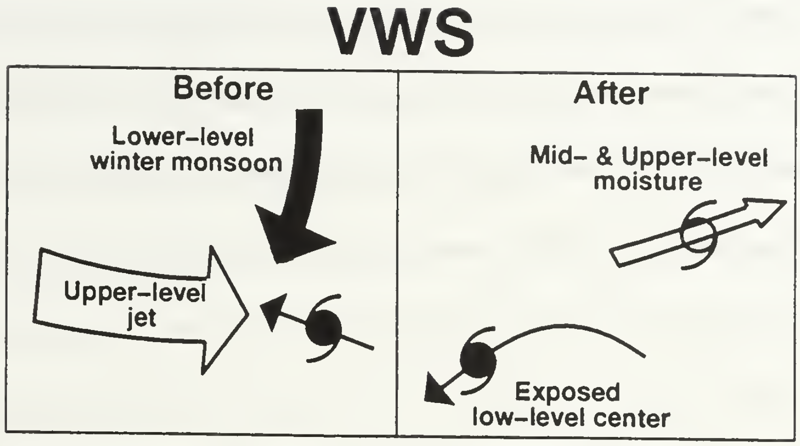


Figure 12. Conceptual model of Vertical Wind Shear (VWS). Upper-level southwesterlies advect the mid- and upper-level moisture northeastward while lower-level northeasterlies of the winter monsoon push the exposed low-level center of the TC to the southwest. Although the TC usually stays in S/DR during the entire time, the track exhibits a sudden turn.

the Philippines from the east, winter TCs often encounter the combination of strong upper-level southwesterlies and lower-level northeasterlies of the winter monsoon. The upper-level, warm core of the TC may be transported off to the northeast while the lower-tropospheric remnants of the TC make a possibly unexpected turn to the southwest.

2. Additional studies

Given the Systematic Approach knowledge base from the WPac, other studies analyzed the performance of official and objective forecasts that comprise phase II of the flowchart (Fig. 2). Webb (1996) documented differing levels of forecast difficulty in terms of the climatology-persistence (CLIPER) forecast performance in the various synoptic patterns and regions. He also compared official JTWC and CLIPER forecast errors to illustrate the level of skill in the various synoptic patterns and regions. This study was important in identifying the difficult forecast scenarios in which the current forecast

procedure has low skill and opportunities for improvement exist. Summaries of the NOGAPS and other objective aid track forecast biases have been provided to the JTWC on an informal basis. These studies are expected to be published soon.

The first application of the Systematic Approach in ECPac (White 1995) proved that some parts of the meteorological knowledge base and some conceptual models were transportable. White examined four seasons (1990-93) and determined that, just as in WPac, all scenarios could be classified in four synoptic patterns and about a dozen transitional mechanisms that explained TC track changes. However, modifications to some of the synoptic patterns, synoptic regions, and transitional mechanisms were required.

C. PLAN OF THESIS

This thesis will first revise and extend the White (1995) classifications for ECPac TCs based on more recent knowledge. An additional goal is an evaluation of the numerical guidance, which is phase I of the Systematic Approach flow chart (Fig. 2). In the numerical guidance phase, the TC-environment conceptual models utilized by White have been modified based on western North Pacific and Southern Hemisphere (Bannister et al. 1997) studies. Studies in these other basins, including the Atlantic, South Indian, and South Pacific, have helped clarify the synoptic patterns and regions of ECPac by putting them into a comprehensive, global context. More cases have been examined with the addition to the database of three more TC seasons (1994-96).

Chapter II will explain the methodology, including the resources available and some nuances used in the subjective classification of synoptic patterns and regions. The TC-

environment conceptual models for the ECPac will be presented and compared with the above WPac models in Chapter III. A number of synoptic analysis sequences will be presented to illustrate the environment structure and transitional mechanisms characteristic of the ECPac. Finally, Chapter IV will provide concluding thoughts and plans for future research.

II. METHODOLOGY

A. RESOURCES

1. Synoptic Analyses

The Systematic Approach environment structure conceptual models have been developed based on the U. S. Navy Operational Global Atmospheric Prediction System (NOGAPS) analyses from the Fleet Numerical Meteorology and Oceanography Center (FNMOC), Monterey, California. Beginning in June 1990, synthetic observations have been included in the NOGAPS analyses to improve the TC location and structure representation. These synthetic observations for eastern (central) North Pacific TCs have been based on the NHC (CPHC) warning messages. Since October 1994, the synthetic observations have included an adjustment to make the average flow in the region of the TC agree with the recent 12-h motion of the storm as contained in the warnings. The synthetic observations, any rawinsondes or other observations, and a 6-h NOGAPS forecast are blended in the data assimilation system to provide the initial conditions for the global model forecast. Although the 500-mb streamline and isotach analyses are typically used to characterize the synoptic pattern/region that determines the steering flow, analyses at 700 mb or lower may be used when the TC is weak or vertical wind shear has affected the upper-tropospheric structure. An archive of NOGAPS analyses and forecasts each 12 h is maintained at the Naval Postgraduate School.

2. TC Positions and Tracks

The final best tracks as determined by NHC and CPHC (Fig. 1) of the seven years (1990-96) provide the ground-truth for this research. Position and storm intensity are provided every 6 h, and storm speed and direction are determined from the straight-line distance travelled during the previous 6 h. The current (asterisk) and preceding three 12-h positions (dots) are plotted on the synoptic analyses to serve as a visual guide as to the current position and recent motion of the TC (Fig. 13a). The TC number for the season is plotted above the current position, while intensity (translation speed) is plotted to the upper-right (right) of each position.

3. Satellite imagery

The Naval Postgraduate School maintains an archive of Geostationary Observational Environmental Satellite (GOES) full disk and eastern North Pacific sector visible and infrared imagery (Fig. 13b). At least one and sometimes two images a day are available. The NHC kindly provided hard copies of images to fill in data voids.

4. Formal reports

Post-storm reports filed by NHC and CPHC forecasters provide the storm history, including unusual motion and possible causes.

B. PATTERN/REGION CLASSIFICATION

For every 12-h NOGAPS analysis in which a TC exists, a synoptic pattern/region combination is assigned to classify the environment structure of the TC. When a TC is clearly in one synoptic pattern/region, only that combination is recorded. If a TC is

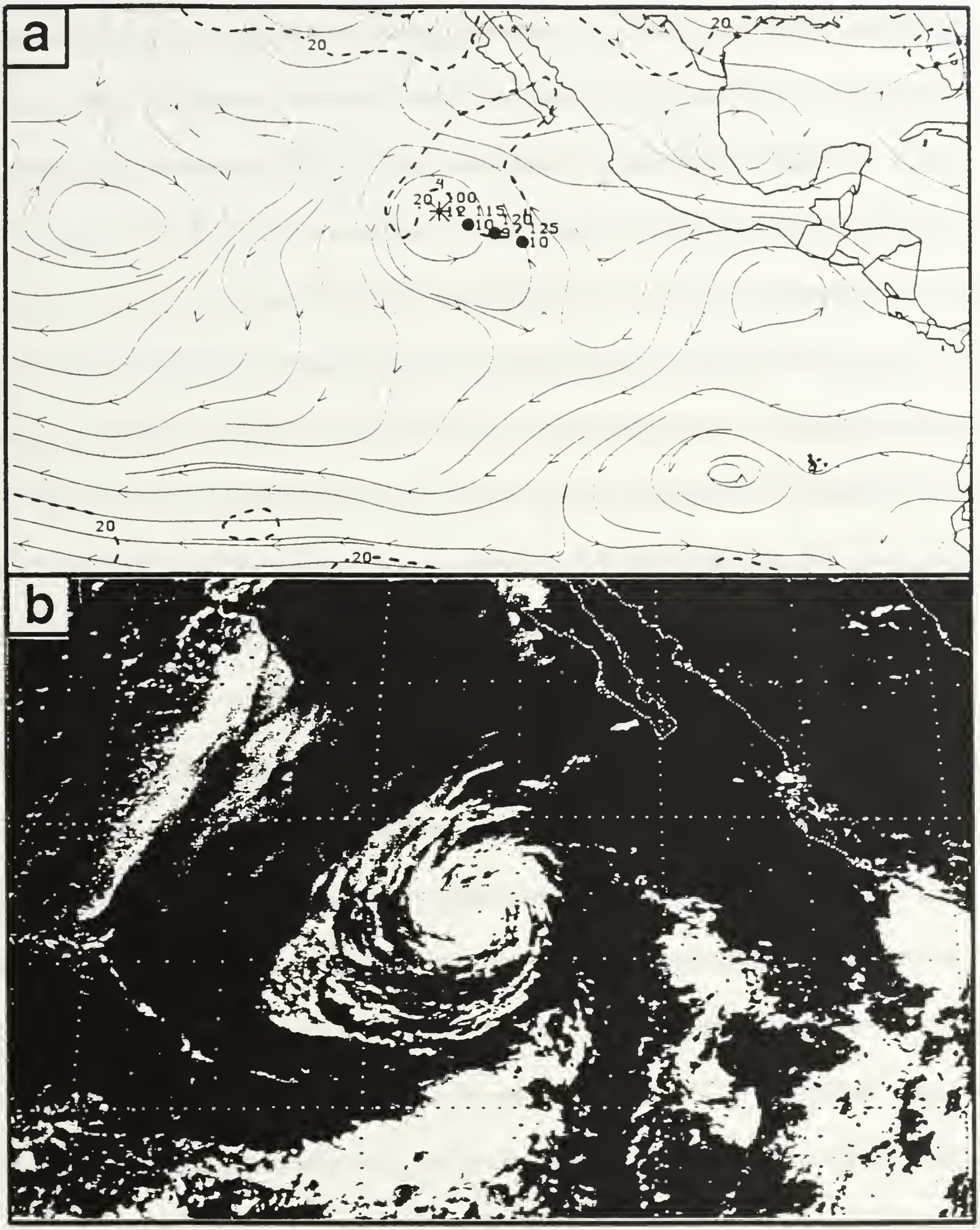


Figure 13. (a) NOGAPS 500 mb analysis for 00 UTC 29 June 1992. Hurricane #4 Celia is depicted. The current position is depicted by an asterisk, and the three preceding 12-h positions are indicated by dots. The TC number is above the asterisk. TC intensity (speed) is to the upper-right (right) of all positions. (b) GOES visible image for 1730 UTC the previous day.

undergoing a transition from one pattern/region to another, then both pattern/region combinations are recorded, with the initial combination always recorded first, even if the TC is almost in the second patten/region. Only when the TC finally completes the transition is the subsequent pattern/region recorded alone. On any single 00 or 12 UTC analysis, more than one TC may be present, and a classification is made for each TC.

In this retrospective determination of the synoptic pattern/region for ECPac TCs, important information is available that the operational forecaster does not have in real-time. Both the final best track and post-storm report are available to describe the scenario. The objective of this study is to determine the *best* description of the TC environment to build the foundation upon which all future real-time classification can be based. It is not expected that the forecaster will properly assign the TC environment every time. Just as the forecaster re-evaluates the recent positions in light of new positions to form a working best track, the forecaster may have to also re-evaluate the recent synoptic pattern/region assignment. White (1995) and Kent (1995) examined the reproducibility of the Systematic Approach in terms of determining the current synoptic pattern/region of a TC for four years (1990-93) in a real-time basis with no knowledge of future motion. Three trainees in the Systematic Approach correctly determined 77.5% of all 12-h classifications. Recent modifications to the final classifications would make that result even higher. This encouraging result validates the potential for the Systematic Approach.

Although analysts incorporate all available data to build the final best tracks, they sometimes do not have enough data to assign accurately or confidently TC positions when

TCs are developing, especially from large depressions. Satellite imagery often has large, sloppy areas of convection with perhaps more than one possible center. The centers of decaying TCs may also be difficult to determine. To avoid classifying the pattern/region for the wrong center, or trying to explain unusual false or actual mesoscale motions, the environment structure is not classified unless the TC intensity is 25 kt or greater.

As stated above, the Systematic Approach numerical analysis guidance knowledge base is built upon the subjective determination of synoptic patterns and regions as depicted by NOGAPS analyses. However, cases may be found in which the TC motion and the numerical synoptic analysis do not physically agree. If the TC is weak, then perhaps the warning position and recent past motion vector should be questioned. Oftentimes, data limitations or vagaries of the numerical analysis may result in inaccurate depictions of the TC environment. For instance, the coarse resolution of the numerical model will typically lead to an underestimate of TC intensity and an overestimate of TC size, which tends to overamplify the Rossby wave dispersion and drive the RMT transitional mechanism too strongly. The limited data and coarse resolution of the model may also cause developing anticyclones or cyclones near a TC to be missed, or the analysis may not depict the circulation feature until after it has already affected the TC. The final synoptic pattern/region classification is based upon the actual environment scenario, which in some cases as mentioned above, lead to the rare times when the classification may not seem to be consistent with each NOGAPS analysis.

III. EASTERN AND CENTRAL NORTH PACIFIC KNOWLEDGE BASE

A. KNOWLEDGE BASE COMPONENTS

The ECPac TC and environment structure knowledge base (Fig. 14) to be used in phase I of the forecasting process has some changes from that initially introduced in the WPac (Fig. 3). Because TC structure (Fig. 14, upper right) has not been quantitatively examined here, no changes are made. However, the replacement and modification of some environment structures and transitional mechanisms are required. In terms of environment structure, a new Low (L) synoptic pattern replaces the G pattern, and two synoptic regions, Ridge Poleward (RP) and Ridge Equatorward (RE) replace the DR region (Fig. 14, upper left). The creation of the L pattern has ramifications for the environment effects of transitional mechanisms (Fig. 14, lower left). The TC-environment transformations called RTF and MTI are not observed in ECPac. New mechanisms called Monsoon Trough Formation (MTF) and Orography (ORO) are observed (Fig. 14, lower right). This chapter will provide more details concerning the environment structure and transitional mechanisms that comprise this knowledge base.

B. ENVIRONMENT STRUCTURE

1. Midlatitude Importance

The general circulation has important variations across the North Pacific (Fig. 15). During the primary WPac typhoon season, the large temperature gradient between warm south Asia and relatively cold Siberia establishes a strong zonal jet in the midlatitudes.

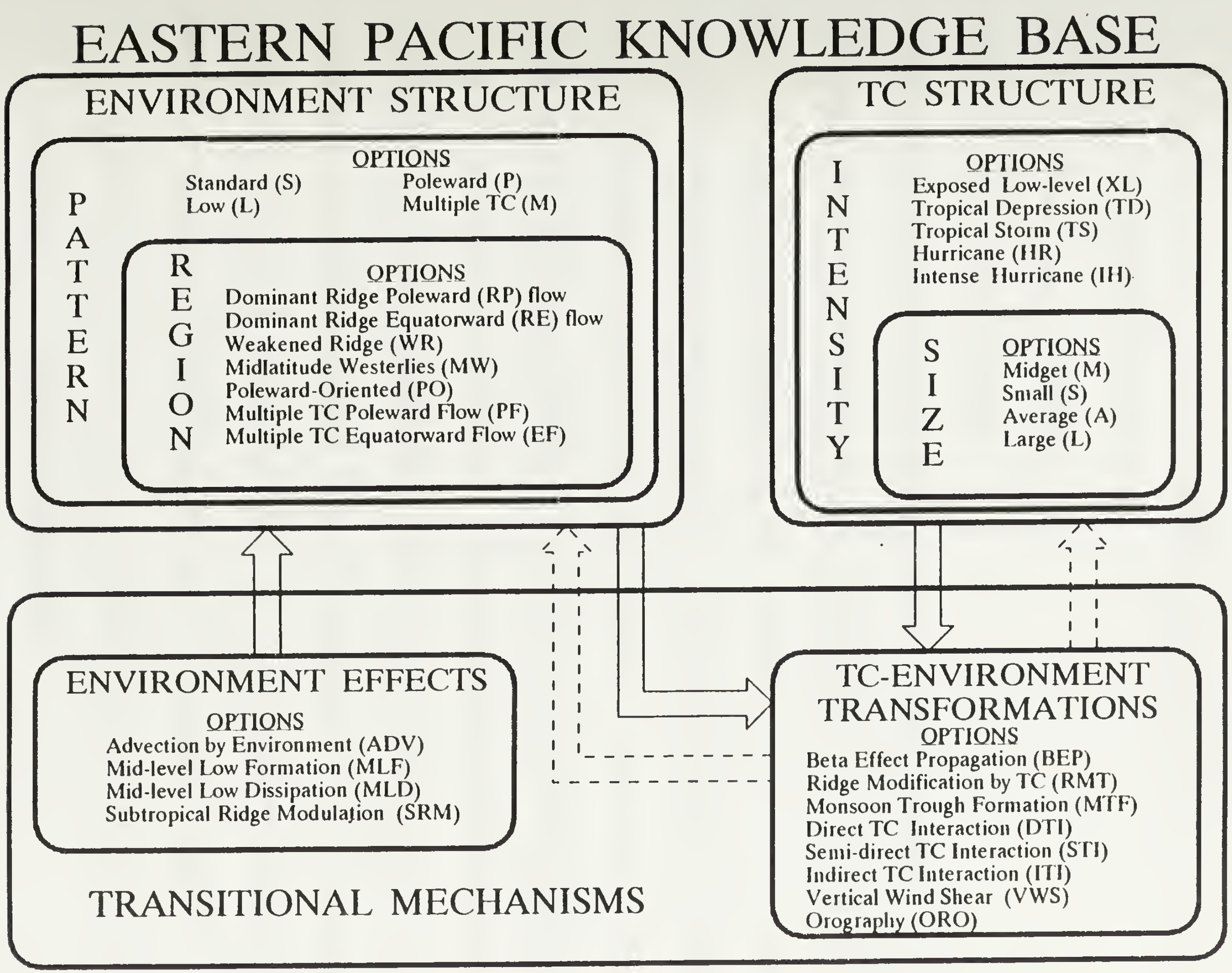


Figure 14. Systematic Approach knowledge base conceptual framework, as in Fig. 3, except for the eastern and central North Pacific.

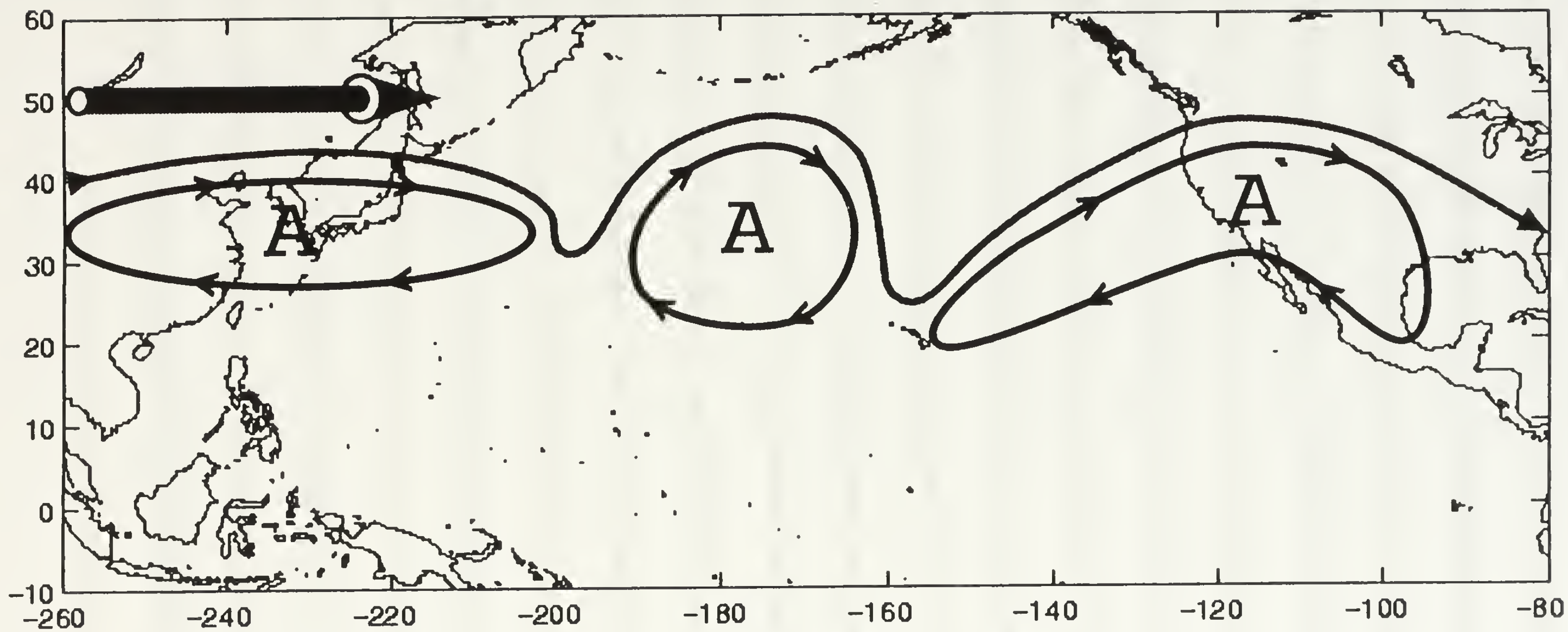


Figure 15. Schematic of the mid-tropospheric subtropical anticyclones (A) and midlatitude wave structure over the North Pacific during the summer. The solid arrow represents a strong westerly flow in association with the Asian summer monsoon.

Hence, the STA is also zonally oriented, it is strongly anchored to the Asian continent, and it extends eastward over the western North Pacific. This circulation is illustrated in Fig. 4a by the long, zonal STA of the Standard (S) synoptic pattern for the WPac. Trade wind easterlies equatorward of the STA advect the majority of storms to the west in the Dominant Ridge (DR) synoptic region, which implies the TC track is determined primarily by the strength of the STA poleward of the TC. However, the strong jet establishes the steering flow within the Midlatitude Westerlies (MW) synoptic region poleward of the STA.

Passing midlatitude troughs (ridges) erode (strengthen) the STA, but rarely do they obliterate or move the strong STA in WPac. However, the meridional amplitudes of midlatitude waves increase as they move eastward across the North Pacific. The strong meridional temperature gradient does not exist in the middle of the Pacific Ocean, and the STA is not as strong. Although the STA in the central North Pacific is a semi-permanent feature, it is usually weaker, more circular in shape, and more easily modulated by passing midlatitude waves than in WPac (Fig. 15). In the eastern North Pacific, the effects of the North American continent downstream play a role, with the STA strongly anchored over the Southwestern Desert of the U.S. Over the continent, this portion of the STA is part of the downward flow of the Hadley cell even though it is above the heat low over the desert. Also, the orientation of the lower-tropospheric heat low and mid-tropospheric STA is along Mexico and Central America (i.e., southeastward rather than eastward). With this STA tilt, the TC steering flow equatorward of the STA is toward the northwest.

The STA extends from North America westward over the Pacific, but the large amplitude upper-troposphere lows and troughs over the eastern North Pacific to the west of the STA center keep the STA from being zonal. Upper-tropospheric lows often dig equatorward to (or below) the latitude of the STA axis, and the STA that extends to the west is forced to be tilted toward the southwest (Fig. 15). One consequence of this observed NE-SW tilt of the STA is a poleward transport of angular momentum from the trade wind easterlies source to the midlatitude westerlies sink. The Rossby wave dispersion concept can also be applied here. The upper low orients the vorticity pattern such that negative vorticity advection (NVA) is to the southeast, which tends to build an anticyclone there. This anticyclone becomes a part of the STA that then extends to the southwest, and creates a region equatorward of the STA with southwestward steering.

Forecasters in WPac must vigilantly watch for passing midlatitude waves to forecast correctly the creation of breaks in the STA or strengthening of the STA. As described in Chapter I, the Subtropical Ridge Modulation (SRM) transitional mechanism may change the environment structure to either allow or inhibit recurvature of a TC by weakening or strengthening the STA poleward of the TC. In ECPac, the upper-tropospheric waves are large, so that they may actually determine the orientation of the STA. Thus, ECPac TCs equatorward of the STA are subject to varying orientations of steering flow. Recognizing the orientation of the STA is therefore critical for predicting the TC track direction.

2. Synoptic Patterns and Regions

a. Standard Pattern

(1) Conceptual model. The ECPac Standard (S) pattern is one of two synoptic patterns to undergo a significant modification from the original WPac model. As described above, the strength of midlatitude waves strongly modulate the actual shape of the STA. Although the STA can occasionally become zonally oriented as in the WPac, this scenario is rare. Instead, the STA is usually tilted, which requires a new S pattern model with new synoptic regions (Fig. 16).

The larger, bowed anticyclone of Fig. 16 depicts the same anticyclone positioned over North America as in Fig. 15. The STA extends to the southeast over Mexico and to the southwest over the Pacific, oftentimes as far as Hawaii. The southwestward extent of the STA is dependent upon the location and strength of midlatitude waves. Equatorward of the STA axis, trade wind easterlies dominate, just as in WPac, except that the change in orientation of the STA in its eastern and western branches causes a marked change in environmental steering flow. The difference is enough to warrant the separation of the single Dominant Ridge synoptic region of the WPac (Fig. 4a) into two distinct regions (Fig. 16).

The region typically on the southeastern side of the bowed anticyclone is characterized by southeasterlies driven primarily by the strong STA. Because of this strong STA, and since the environmental steering flow has a poleward component, the synoptic region is called Ridge Poleward (RP). Superposition of the TC cyclonic circulation

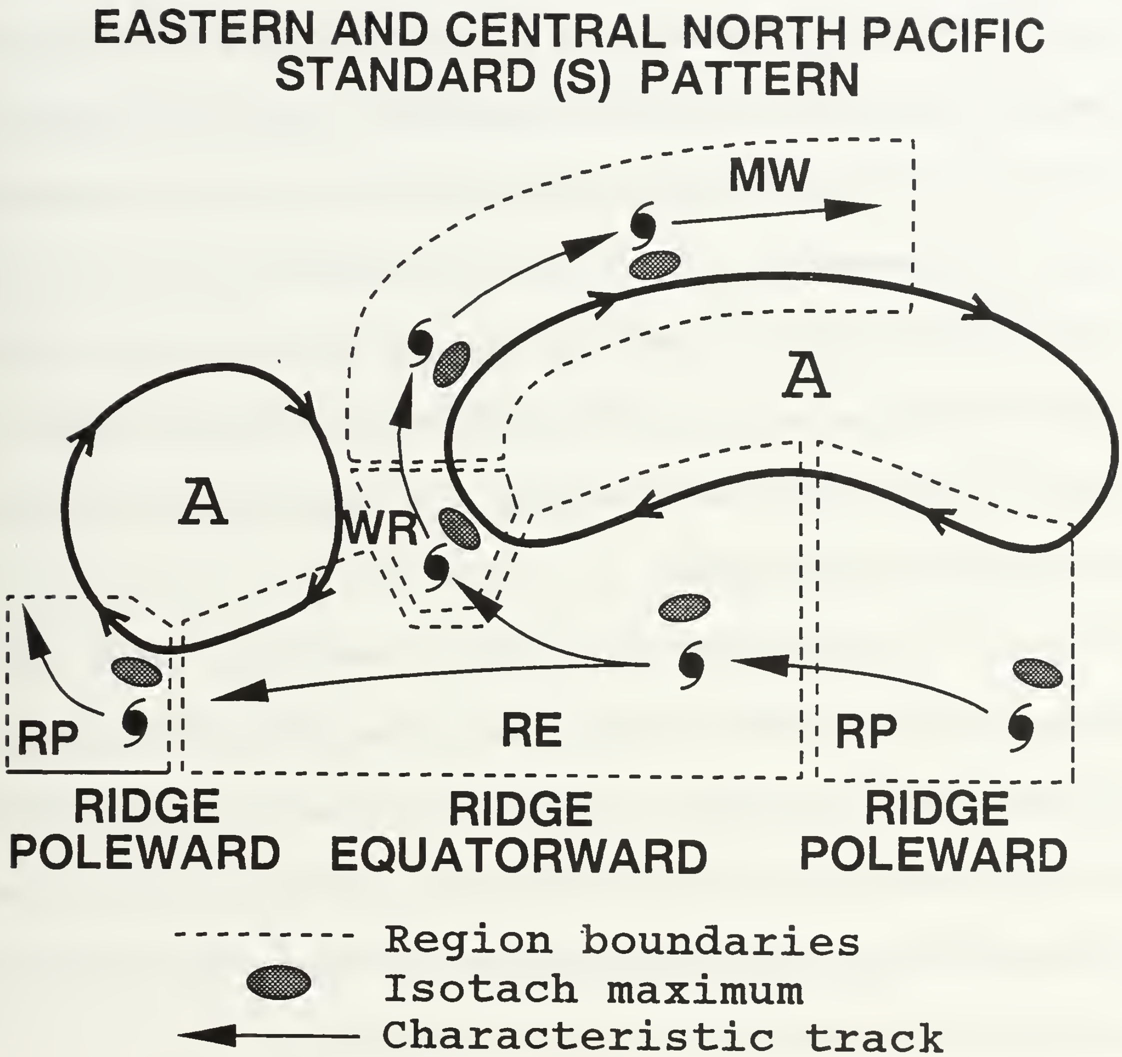


Figure 16. Conceptual model of Standard (S) synoptic pattern for the Eastern and Central North Pacific. Thick solid streamlines represent the 500-mb environmental flow after removal of the TC circulation. Light solid arrows illustrate characteristic tracks. Isotach maxima relative to the TC positions are indicated by shaded elliptical regions. Light dashed lines enclose the Ridge Poleward (RP), Ridge Equatorward (RE), Weakened Ridge (WR), and Midlatitude Westerlies (MW) synoptic regions.

with this environmental flow leads to an isotach maximum on the northeast side of the TC (Fig. 16). As the background flow and the beta-effect propagation are in the same direction toward the northwest, TCs that form or move into the RP region will tend to move toward the northwest. The Ridge Equatorward (RE) synoptic region, which is to the southwest of the North American STA, is characterized by deep trade wind easterlies with an equatorward component. The background flow and northwestward beta-effect propagation vector are not in the same direction. If the tilt of the STA is large, then the TC may be driven south of west. If the tilt is not so large, or if the TC is large, then the TC may move west or even north of west. Given a strongly tilted STA as in Fig. 16, the isotach maximum will be to the northwest of a TC in the RE region.

If, as in the WPac, the STA is strong with no break, the two anticyclones in Fig. 16 would be connected. However, passing midlatitude troughs or the PVA ahead of the TC may weaken the STA and create a break, which is the Weakened Ridge (WR) synoptic region (Fig. 16). The WR region is essentially a col in the STA, and it is characterized by slow environmental steering flow. The isotach maximum would shift to northeast (or east, depending upon the STA orientation) of the TC.

If the TC moves poleward from a break in the STA, it will move into the Midlatitude Westerlies (MW) synoptic region, with the maximum isotach shifting to the southeast side of the TC (Fig. 16). The S/MW pattern/region is essentially the same as that for the WPac, except that the translation speeds of the TC are less owing to the reduced environmental steering flow. The WPac MW regions are characterized by the strong flow

of the zonal jet depicted in Fig. 15. In the ECPac, when TCs move into the S/MW region, they usually do so because a trough has broken the STA. Therefore, the TC is at the southern end of a trough, which has weak flow. Although a TC in the ECPac may occasionally be advected by a strong midlatitude jet and move quickly in the S/MW pattern/region, on average it moves slower than a TC in the WPac.

The western anticyclone in Fig. 16 may represent either a separate circular Central Pacific anticyclone or the unbroken (no WR) extension of the North American STA well out into the Pacific Ocean. TCs on the southeast side of this Central Pacific anticyclone are in northeasterly flow and are in the RE synoptic region. If a TC is on the southwest side of this western anticyclone, the environmental flow changes to one of southeasterlies. This synoptic region is again referred to as Ridge Poleward. Although this RP region is similar to WR in the schematic, there are differences. The WR region is situated between two anticyclones and is a weakened environmental steering flow within a large ridge. By contrast, the RP synoptic region of the Central Pacific does not have another anticylone to the west. Rather the southeasterlies usually extend a considerable distance to the west of the TC. Sometimes, the Central Pacific anticyclone stretches to the northwest and actually connects to the eastern edge of the WPac STA. The environmental flow does not decrease in the western RP region as much as in the WR region, which means that the TC translation speed usually remains consistent with previous motion, rather than slowing as in the WR region. In both cases, the isotach maximum shifts to the northeast side of the TC, so this is not a distinguishing characteristic.

In a typical long-lasting straight-runner case, a ECPac TC will form in the RP region and begin moving toward the northwest. As the TC reaches the apex of the STA, it will turn toward the west. Usually the equatorward component of the background flow in the RE region cancels the poleward component of the beta-effect propagation and the TC moves in a long westward track. Eventually, the TC will turn to the northwest again if it reaches the RP region on the southwestern side of the Central Pacific anticyclone.

In a recurvature sequence, the location of the WR region is critical. The conceptual model in Fig. 16 depicts the WR in the western section of the STA. In reality, the STA can be broken anywhere along its length. If the WR region is at the STA apex, the TC may move directly from the RP into the WR region.

Finally, note how much farther equatorward the TC positions in the eastern RP and RE are from the STA axis than those in the other synoptic regions (Fig. 16). The center of the STA over the southwestern United States is far to the north of the TC generation area west of the Central American coast. However, the trade wind easterlies extend to the south for a long distance. As the TC moves west or northwest, it moves closer to the STA axis, as indicated in the conceptual model.

(2) Analysis examples. A representative NOGAPS streamline and isotach analysis for a TC in the Standard/ Ridge Poleward (S/RP) synoptic pattern/region combination is shown in Fig. 17. The structure of the entire STA is much like the classic S pattern conceptual model in Fig 16. The large, bowed North American STA, which is centered over the California-Arizona border, is clearly depicted. The eastern branch of the

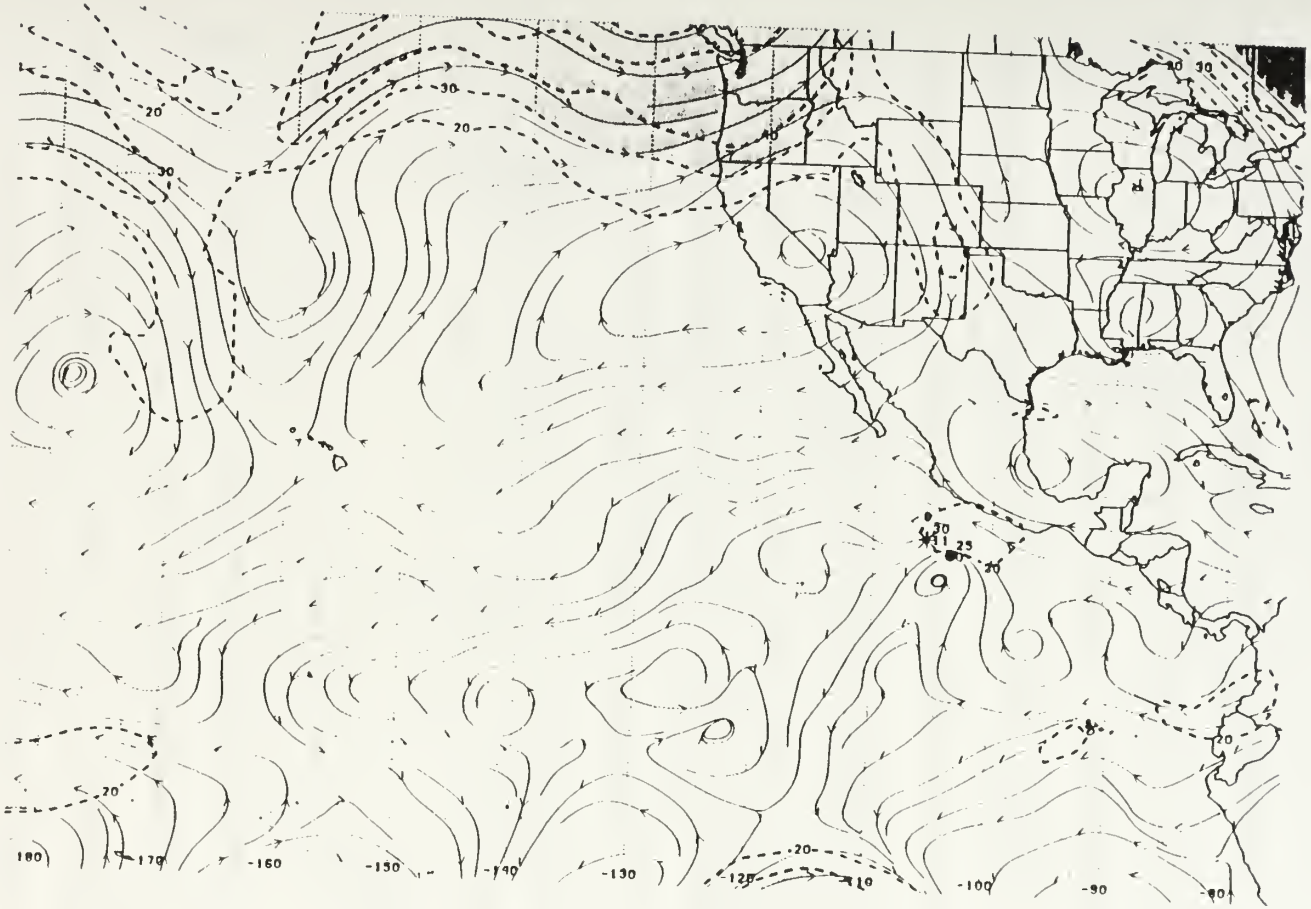


Figure 17. NOGAPS 500-mb streamlines (thin solid) and isotachs (thick dashed) at 10-kt intervals beginning at 20 kt at 00 UTC 31 August 1996. The current TC position (TD 08E) is indicated by an asterisk and the prior -12 h position is given as a dot. Because TD 08E had formed just 12 prior, no -24 or -36 h position is given. TC number is above the current position while TC intensity (translation speed) is to the upper-right (right) of all positions.

STA extends southeastward over Mexico while the western branch extends southwestward to Hawaii. A midlatitude trough is creating a break just west of Hawaii, which then separates a circular Central Pacific STA from the North American STA. TD 08E (eventually TS Elida) of 1996 is imbedded in the southeasterly background flow of the RP synoptic region. The TC is tracking toward the northwest at 11 kt, with the 20-kt isotach maximum to the northeast of the TC as indicated in Fig. 16.

TD 08E (eventually Hurricane Li) of 1994 is an example of a TC in the strong northeasterlies of the Standard/ Ridge Equatorward (S/RE) synoptic pattern/region combination (Fig. 18). Since the North American STA in this case does not extend southeastward over Mexico, only the Bermuda high provides some southeasterlies over Central America. However, the North American STA does extend southwestward well beyond Hawaii. Since TD 08E is small, it does not have a large beta-effect propagation, and it is simply advected by the environmental flow to the southwest at 15 kt. Notice the 20-kt isotach maximum on the northwest side of the TC is consistent with the RE synoptic region conceptual model (Fig. 16).

The long-lived Hurricane John of 1994 is an example of a persistent straight-runner TC that moved from the S pattern/eastern RP synoptic region, into the RE region, and then into the Central Pacific RP region before travelling on to the WPac. The typical bowed STA depicted in Fig. 19a is consistent with the northwestward motion of TS John in the RP synoptic region. As expected, the 20-kt isotach maximum is to the northeast of the TC. However, notice that the track of John over the previous 36 h had been initially

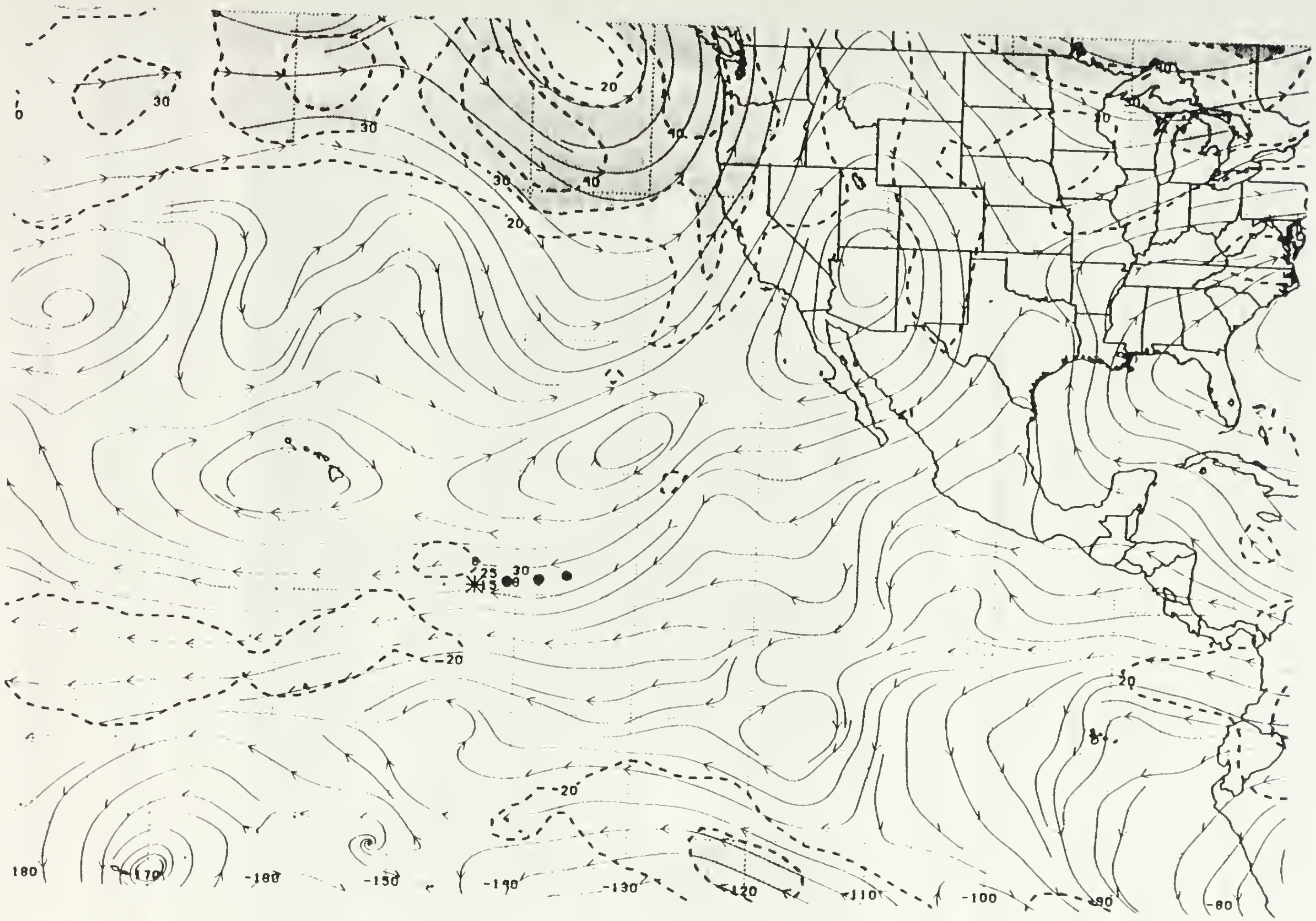


Figure 18. NOGAPS 500-mb analyses as in Fig. 17, except at 00 UTC 4 August 1994.

toward due west, which is unusual for the S/RP region. The cutoff low near 20°N, 137°W had complicated the environmental structure for the previous couple days. While this cutoff low had been to the northwest of the TC, a peripheral anticyclone had developed southeast of the low that is west of the TC. John experienced an ITIE type of transitional mechanism (Fig. 11c) in which the equatorward flow on the eastern side of the peripheral anticyclone replaced the poleward flow of the RP region as the synoptic environment around John. The equatorward component of this flow then cancelled the poleward component of the beta-effect propagation, and John travelled west. In this case, this scenario is not classified as ITIE since another TC is not building the obstructing peripheral anticyclone in Fig. 19a. Rather, a cutoff low that is just considered part of the environment created the anticyclone. Nevertheless, the forecaster should be cognizant of such circulations as they may affect a TC track just as much as an interaction with another TC. By the time of the analysis in Fig. 19a, the cutoff low and peripheral anticyclone have begun to move westward and decrease their influence on John. In the last 12 h, John is being advected primarily by the environmental flow of the RP synoptic region.

Five days later (Fig. 19b,c), Hurricane John is travelling southwestward in the RE synoptic region just southeast of Hawaii. Although the entire STA is not bowed as much as before, the basic configuration is still present, with the RP region over Central America and a RE region that extends from near the Mexican coast to beyond Hawaii. The 130-kt hurricane is being advected to the southwest at 17 kt with the 20-kt isotach maximum north of the TC, as expected from Fig. 16.

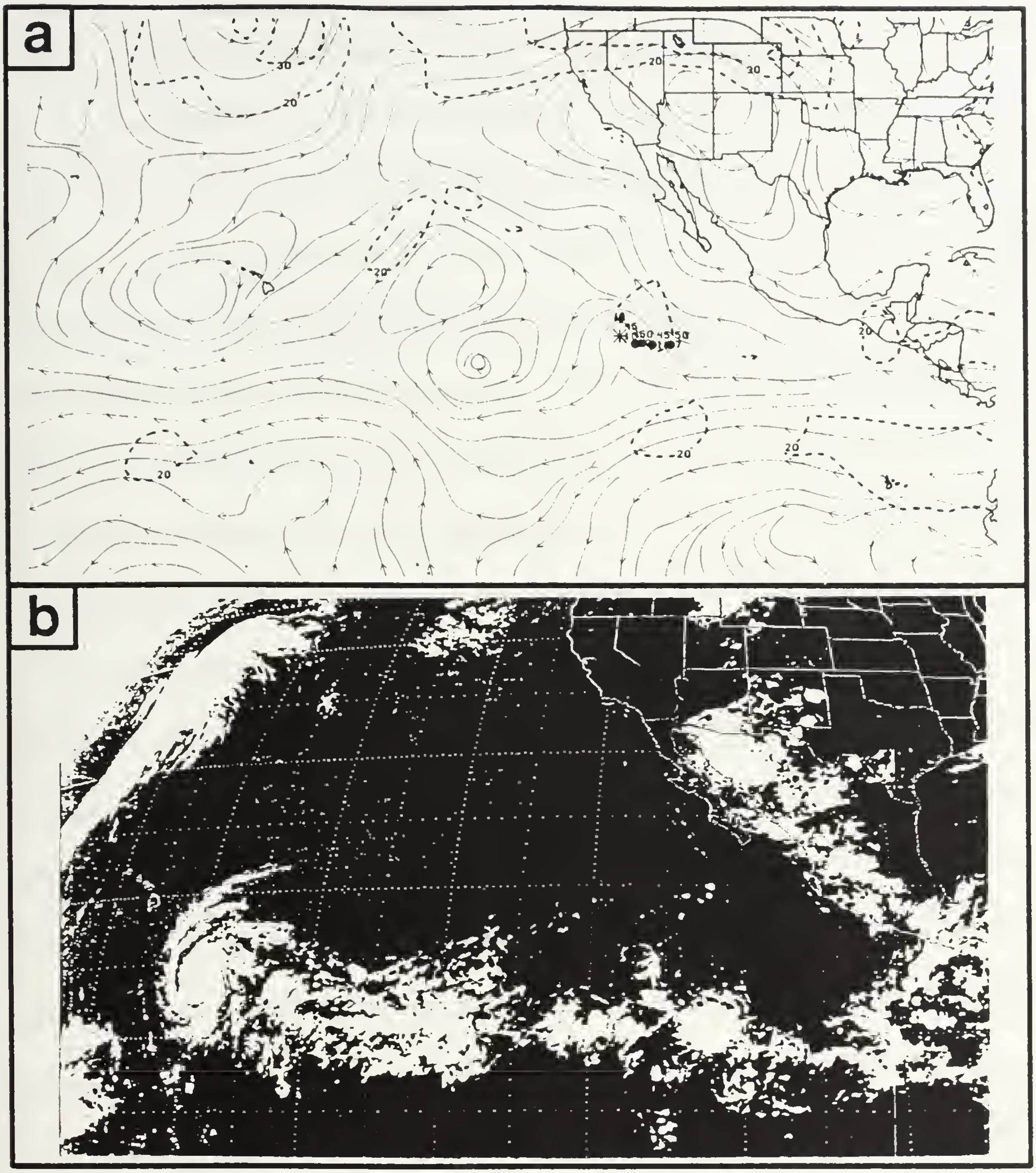


Figure 19. (a) NOGAPS 500-mb analysis as in Fig. 17, except at 12 UTC 17 August 1994. (b) GOES infrared imagery at 05 UTC 22 August 1994.

The transient nature of the ECPac is illustrated in this case. A cutoff low is in the upper left of the GOES imagery (Fig. 19b) and a long cloud band of a cold front is aligned north-northeast to south-southwest just to the east of the low center. Clear skies indicative of an anticyclone lie between the cold front and Hurricane John. This low near 36°N, 170°W (Fig. 19c) appears to be contributing to the STA to the west and northwest of John via Rossby wave dispersion. That is, the peripheral anticyclone associated with the low adds to the already-present STA and helps give the STA its northeast-southwest tilt as far west as the dateline. Similar to Fig. 19a, this is not an ITIE scenario, even though the physical cause and the effect of establishing a south of west steering flow is similar.

Sixty hours later (Fig. 19d), Hurricane John is moving northwestward in the RP synoptic region on the south-southwest flank of the Central Pacific anticyclone. Meanwhile, the midlatitude low and its associated peripheral anticyclone have translated to the northeast (46°N, 163°W). Without the superposition of the peripheral anticyclone, the STA has a more circular shape. Since John is in southeasterly flow, the 30-kt isotach maximum is to the northeast of the TC. Notice that John is not between two anticyclones, as it would be in the WR region. John has currently slowed to 10 kt, which is at the extreme upper end of translation speeds in S/WR. This deceleration is temporary, and John would subsequently remain in the S/RP pattern/region well past the dateline while maintaining an average speed of 13 kt for the next several days (not shown).

The creation of the Standard/ Weakened Ridge (S/WR) pattern/region combination via Beta-Effect Propagation (BEP) is highly dependent upon the amount of

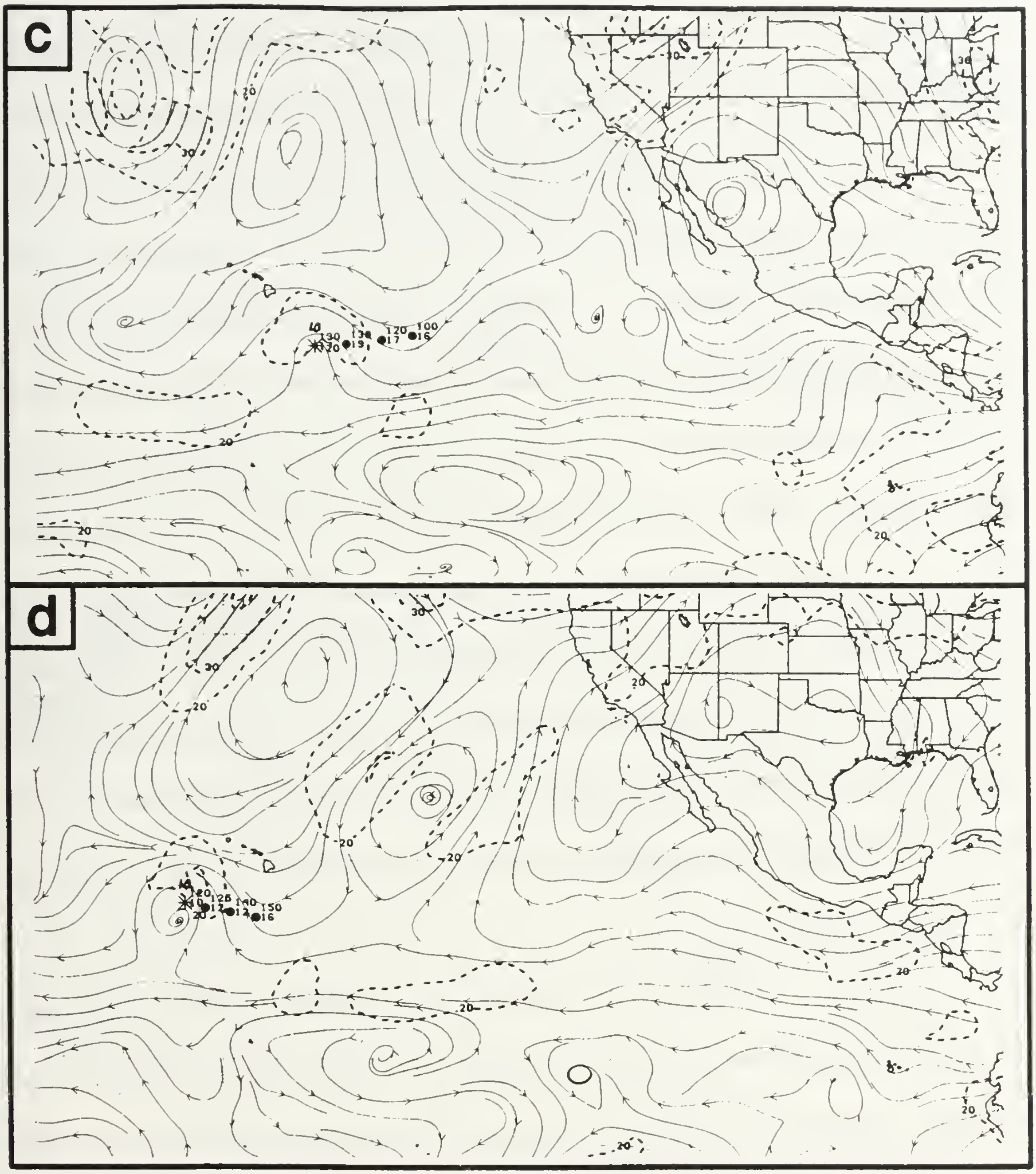


Figure 19. (continued) NOGAPS 500-mb analyses at (c) 12 UTC 22 August and (d) 00 UTC 25 August 1994.

PVA ahead of the TC. More commonly in the ECPac, the break in the STA is created by passing midlatitude troughs via the Subtropical Ridge Modulation by a Trough (SRMT). At 12 UTC 3 July 1994 (Fig. 20a), TD (previously a hurricane) Celia had a peripheral anticyclone to its southeast for 36 h, and yet had not completed a transition from S/RE to P/PO via the Ridge Modification by a TC (RMT) transitional mechanism (Fig. 8). Just 12 h prior, a midlatitude trough had caused a break in the STA to the north of Celia via SRMT, and Celia moved poleward out of the northeasterlies of the RE region and into the WR region between two anticyclones of the northeast-southwest tilted STA. This WR scenario is quite similar to the S pattern conceptual model (Fig. 16). Although TD Celia is moving slowly at 5 kts toward the northwest as expected in the WR region, this slow speed in conjunction with the slow environmental steering flow does not result in a 20-kt isotach maximum to the northeast for this example. Even though an isotach maximum is probably located to the northeast, the wind speed values are just less than the minimum of 20 kt set in the plotting routine.

As previously mentioned, the breaking of the STA by midlatitude troughs is the key determination as to the creation of the WR region. As depicted by the conceptual model (Fig. 16) and the previous example, this typically happens over the Pacific Ocean where the STA is relatively weak. However, midlatitude troughs can be strong enough to modulate the STA even where it is usually strong over the North American continent. At 00 UTC 13 September 1991 (Fig. 20b), a large midlatitude trough has shifted the STA eastward by about 3000 km from its usual position over the southwestern United

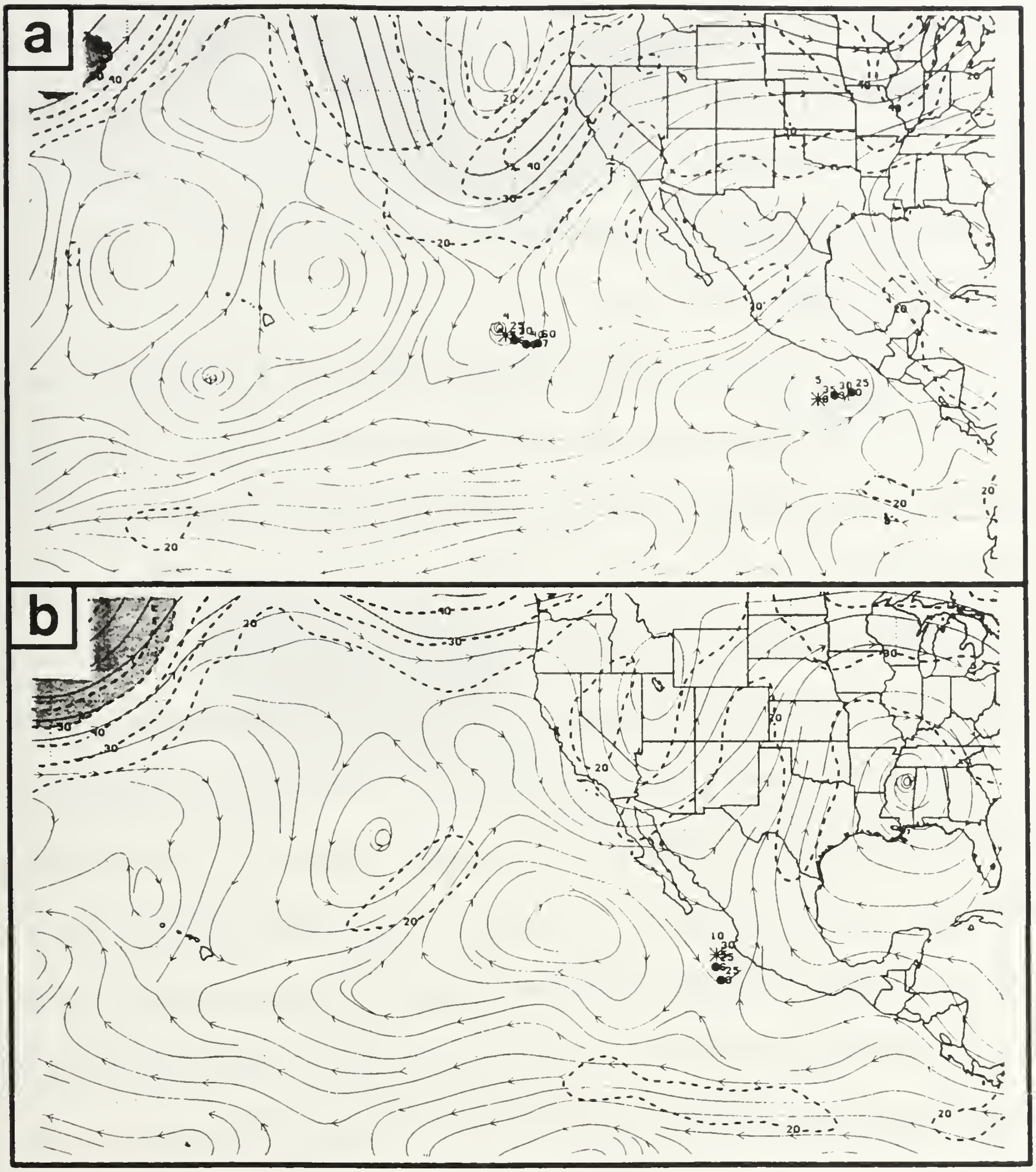


Figure 20. NOGAPS 500-mb analyses as in Fig. 17, except they illustrate S/WR cases at (a) 12 UTC 3 July 1992 (TD Celia is TC #4 in the center; TS Darby is TC #5 to the east) and (b) 00 UTC 13 September 1991 (TD 10E).

States. The TD 10E, which had previously been in the S/RP pattern/region, then moves into the Weakened Ridge created by this trough. The TD translation speed of 5 kt and the poleward track are typical characteristics of TC motion in the S/WR pattern/region. These two examples demonstrate how ECPac forecasters must be wary of the presence of the WR region anywhere along the STA axis.

Just as the S/WR pattern/region analyses showed differences between being over the open ocean or near the continent, so too do S/MW analyses. TS (previously a hurricane) Roslyn at 00 UTC 30 September 1992 (Fig. 21a) is in the S/MW region north of the tilted STA axis and at the base of a midlatitude trough. Notice that the strong jet associated with the trough is far to the north of the TC. Hence, Roslyn is moving slowly east-northeast at 7 kt. The slow environmental steering and translation speed result in no 20-kt isotach maximum near the TC, even though the overall 500-mb flow is similar to the S pattern schematic (Fig. 16). TS (previously a hurricane) Fausto at 12 UTC 14 September 1996 (Fig. 21b) is an example of a TC in S/MW over the continent. The STA does not possess the usual bowed shape as a midlatitude trough extends south over Baja California. Having been caught by the trough and having moved north of the STA axis, Fausto is quickly moving toward the north-northeast at 17 kt. The strong jet of the trough is close to the north of the TC, and the expected isotach maximum associated with TC motion is to the southeast. Although this particular S/MW case has differences from the conceptual model in Fig. 16, the key criteria are that the TC is poleward of the STA axis and has an east of north translation.

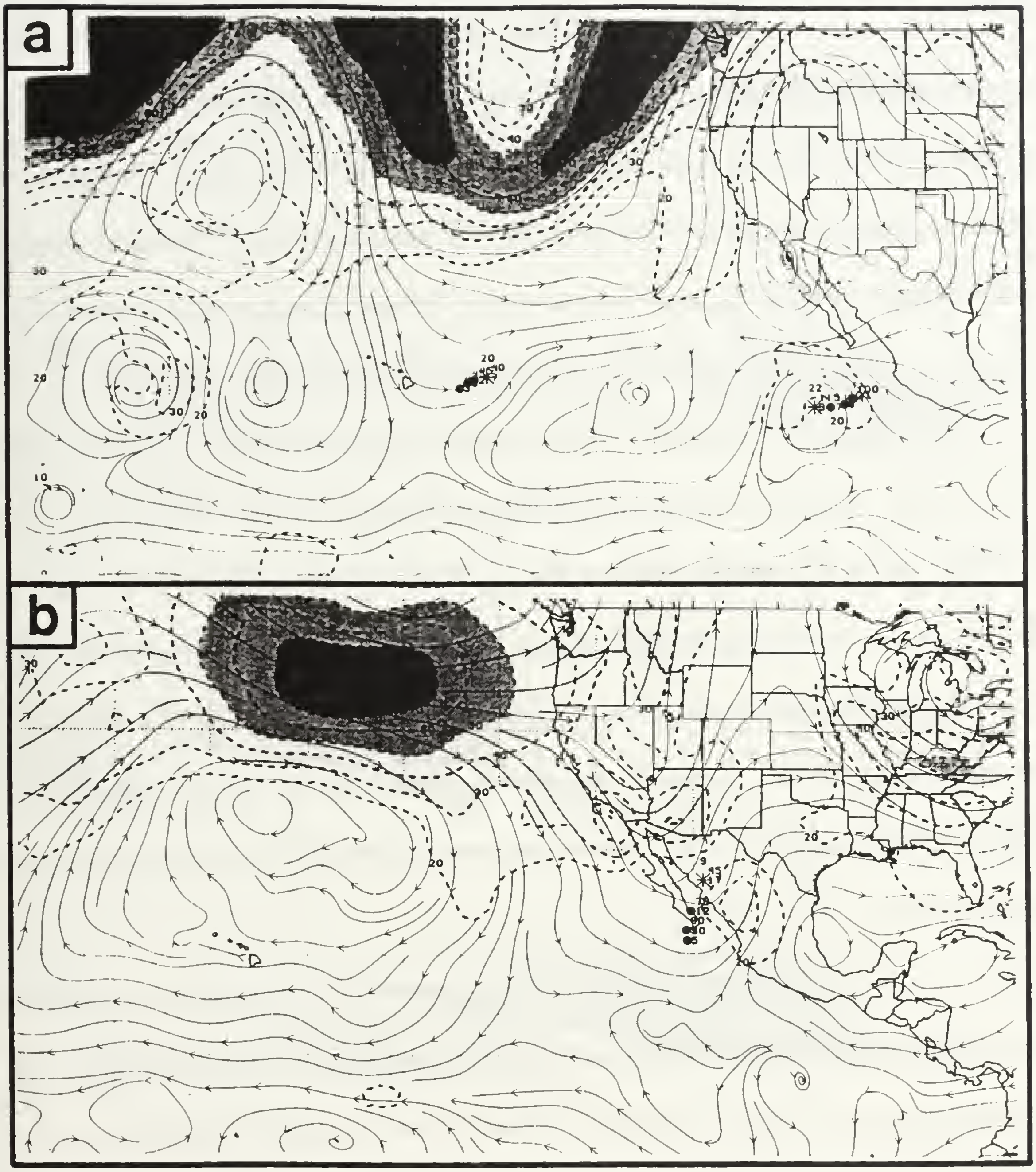


Figure 21. NOGAPS 500-mb analyses as in Fig. 17, except they illustrate S/MW cases at (a) 00 UTC 29 September 1992 (TS Roslyn is TC #20 near Hawaii; Hurricane Tina is TC #22 to the east) and (b) 12 UTC 14 September 1996 (TS Fausto).

(3) Tracks. All tracks while TCs during 1990-96 were in the S/RP pattern/region combination are shown in Fig. 22a. Notice the two clusters of tracks associated with the separate North American and Central Pacific RP regions. Clearly, more tracks are found in the eastern RP region. Most of these tracks are of a moderate length, which indicates that the TCs tend to remain in the S/RP pattern/region for some time. It is emphasized that all of these TC tracks have a characteristic northwest orientation.

The tracks of TCs in the S/RE pattern/region combination (Fig. 22b) are toward the west and, on average, are slightly longer than those in the S/RP region. The tracks of smaller TCs are usually oriented south of west because of the tilt of the STA, or the TC may be undergoing the ITIE process. Larger TCs have a greater BEP, and their tracks tend to be north of west. Notice that the TCs in the RE region are more uniformly spread over the domain, although no cases were found east of 100°W in this sample. Because TCs in both S/RP and S/RE are equatorward of the STA axis, they do not exist north of 30°N.

The small size of, and the short durations in, the S/WR pattern/region are apparent in the short tracks of TCs (Fig. 22c). The direction of the tracks shifts from northward near the North American continent where the STA is broken by deep meridionally-oriented midlatitude troughs (e.g., TD 10E in Fig. 20b) to northwestward over the Pacific Ocean where TCs are moving through the tilted STA (e.g., TD Celia in Fig. 20a). The non-characteristic longer tracks near the center of the domain are results of the SRM

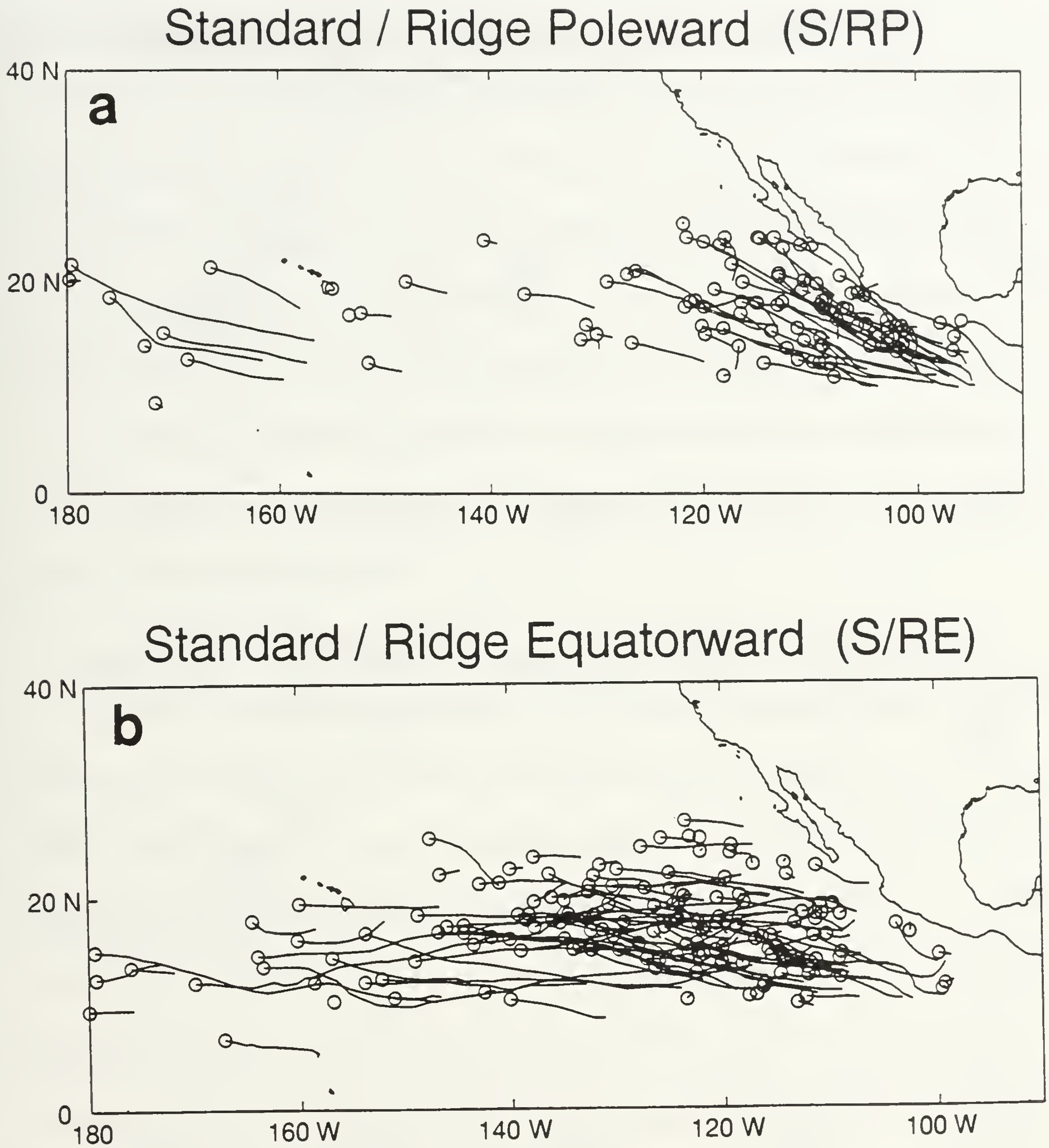
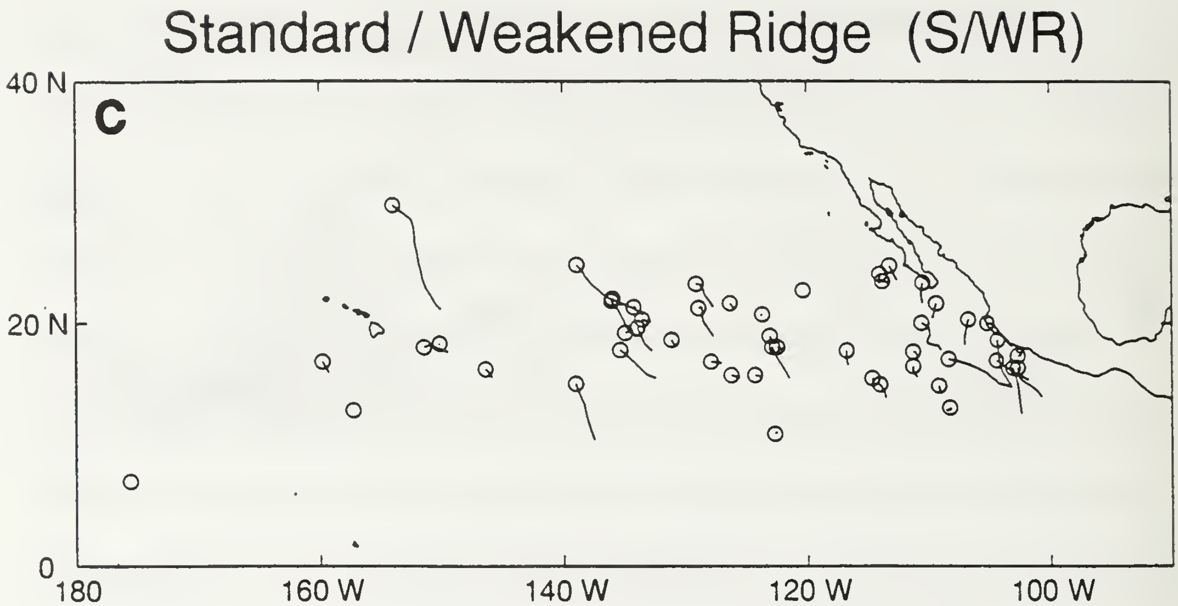


Figure 22. Tracks as in Fig. 1, except only while the TCs were in the Standard (S) synoptic pattern and (a) Ridge Poleward (RP) or (b) Ridge Equatorward (RE) synoptic regions.



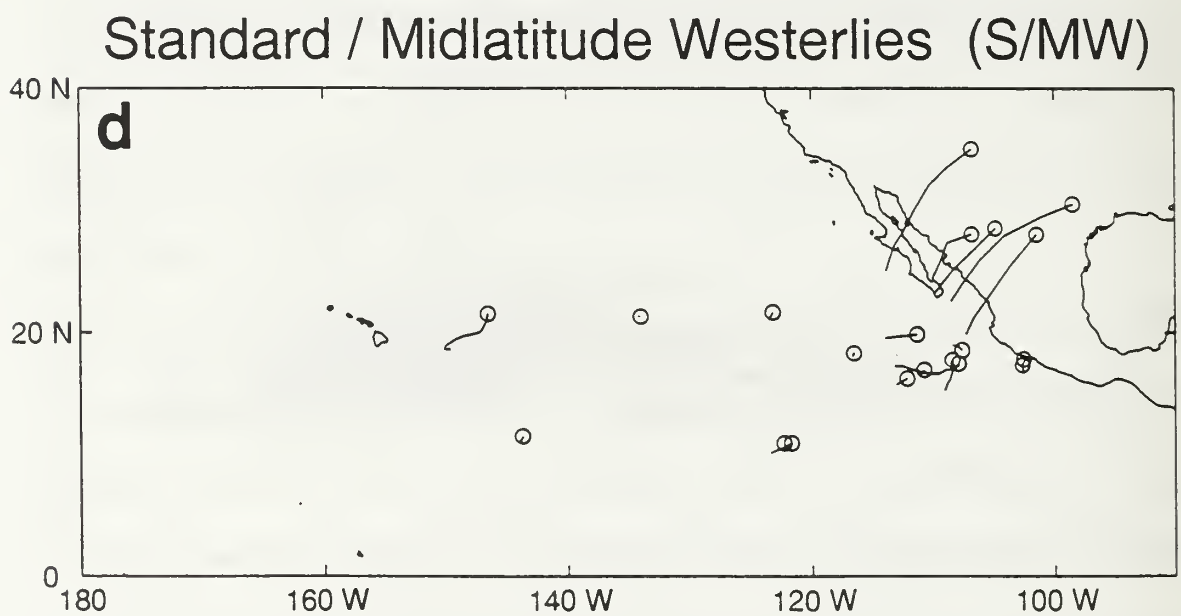


Figure 22. (continued) Tracks in S pattern and (c) Weakened Ridge (WR) or (d) Midlatitude Westerlies (MW) regions.

process in which the midlatitude wave reinforces the STA, and the break in the STA has a larger meridional extent.

The S/MW tracks also exhibit two distinct groups (Fig. 22d). Longer tracks of fast-moving TCs that are moving northeastward tend to be over the continent (e.g., TS Fausto in Fig. 21b). Shorter tracks of slower-moving TCs toward the east-northeast tend to be over the ocean (e.g., TS Roslyn in Fig. 21a). Notice that TCs are not found in the S/MW pattern/region west of Hawaii for this sample. If TCs continue to exist that far west, they tend to be so far south that few midlatitude troughs have sufficient meridional extent to cause a recurvature into the S/MW region. At least in this sample, only the TCs over the continent move much north of 20°N.

b. Poleward Pattern

(1) Conceptual model. The ECPac Poleward (P) synoptic pattern conceptual model (Fig. 23) is essentially the same as that of the WPac (Fig. 4b). In this pattern, a large TC moves poleward while still equatorward of the STA axis owing to a strong peripheral anticyclone to the southeast that causes southerlies over the TC. The only minor difference to the conceptual model for ECPac is that in this 7-y data set a TC was never observed to move into the P/MW pattern/region. Most eastern Pacific TCs dissipate over cold water or in vertical wind shear prior to entering the MW region. Hence, a characteristic track arrow has not been extended into that region. However, the MW region has been included in the conceptual model because such a track still seems physically possible.

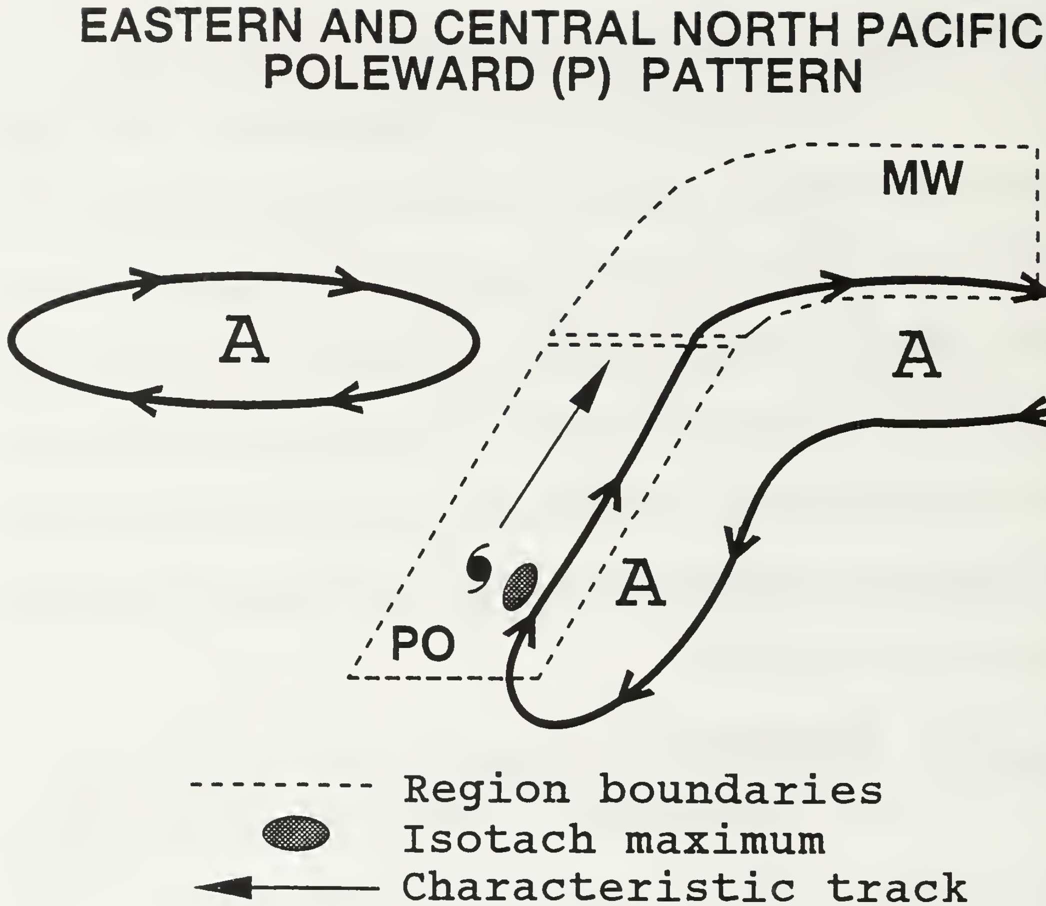


Figure 23. Conceptual model as in Fig. 16, except for Poleward (P) synoptic pattern and Poleward-Oriented (PO) and Midlatitude Westerlies (MW) synoptic regions. None of the TCs in the 7-y sample was observed in the MW synoptic region.

Although TC structure is not a major subject of this study, its importance is not overlooked. A TC must be relatively large, i.e., have strong outer winds, to produce a significant peripheral anticyclone via Rossby wave dispersion. Because the ECPac TC on average is not as large or strong as in the WPac, the likelihood of the P pattern is less. Many times in the 7-y data set, the RMT process is depicted in the NOGAPS

analyses as a peripheral anticyclone that is slowly developing to the southeast of a TC. Because the TC is rarely strong enough, the fledgling peripheral anticyclone often dissipates or is advected to the west by the trade wind easterlies before the ridge structure in the vicinity of the TC can be modified.

(2) Analysis example. TS (previously a hurricane) Boris at 12 UTC 7 June 1990 (Fig. 24) is in the Poleward/ Poleward-Oriented (P/PO) pattern/region. Although a second anticyclone is located to the west-southwest of Boris, the northern cell of the STA has its typical northeast-southwest tilt over the Pacific Ocean. However, the important circulation establishing the steering flow across Boris is not the STA, but rather the peripheral anticyclone, which is connected to the STA and extends to 10°N latitude southeast of the TC. Southerlies on the west side of the peripheral anticyclone are advecting Boris due north at 6 kt. This speed, which is on the slow end of the spectrum for motion in the P/PO pattern/region, and the relatively weak peripheral anticyclone help explain why a 20-kt isotach maximum is not plotted to the southeast of Boris. Otherwise, the analysis is similiar to the P pattern conceptual model (Fig. 23).

(3) Tracks. Although the tracks of TCs in the P/PO pattern/region (Fig. 25) all possess poleward components, the lengths and directions, which range from northwest to due east, exhibit large variability. The spectrum is a result of varying strengths and orientations of the peripheral anticyclone as well as interactions with other TCs. An important characteristic of the P/PO tracks in this 7-y sample is the limited domain in the eastern Pacific in which TCs in this pattern/region are found.

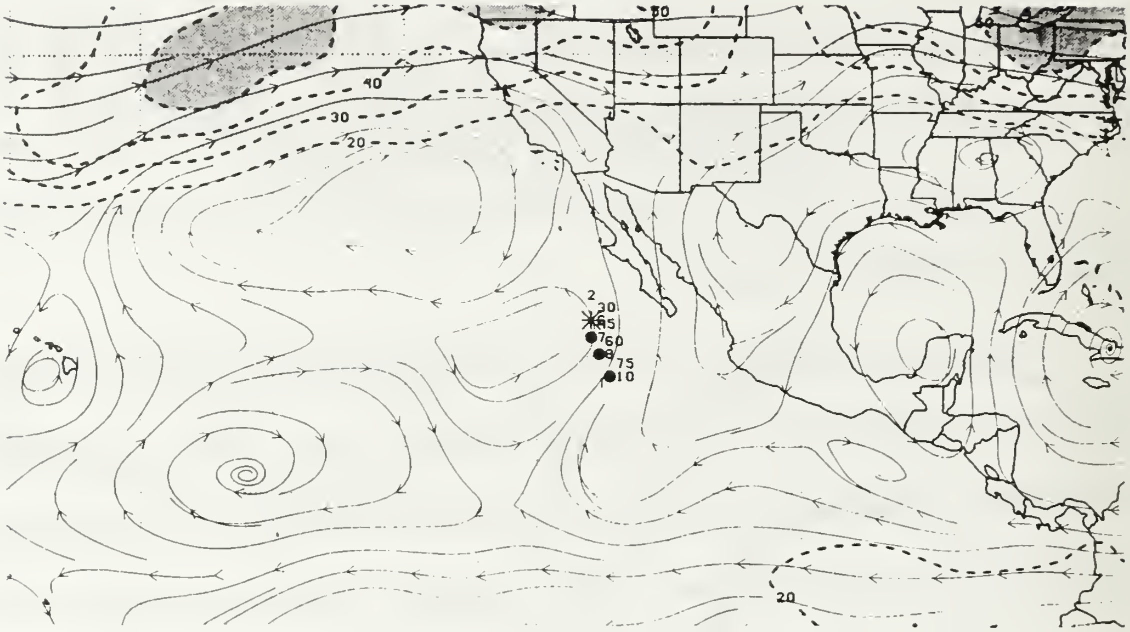


Figure 24. NOGAPS 500-mb analysis as in Fig. 17, except it illustrates a P/PO case at 12 UTC 7 June 1990 (TS Boris).

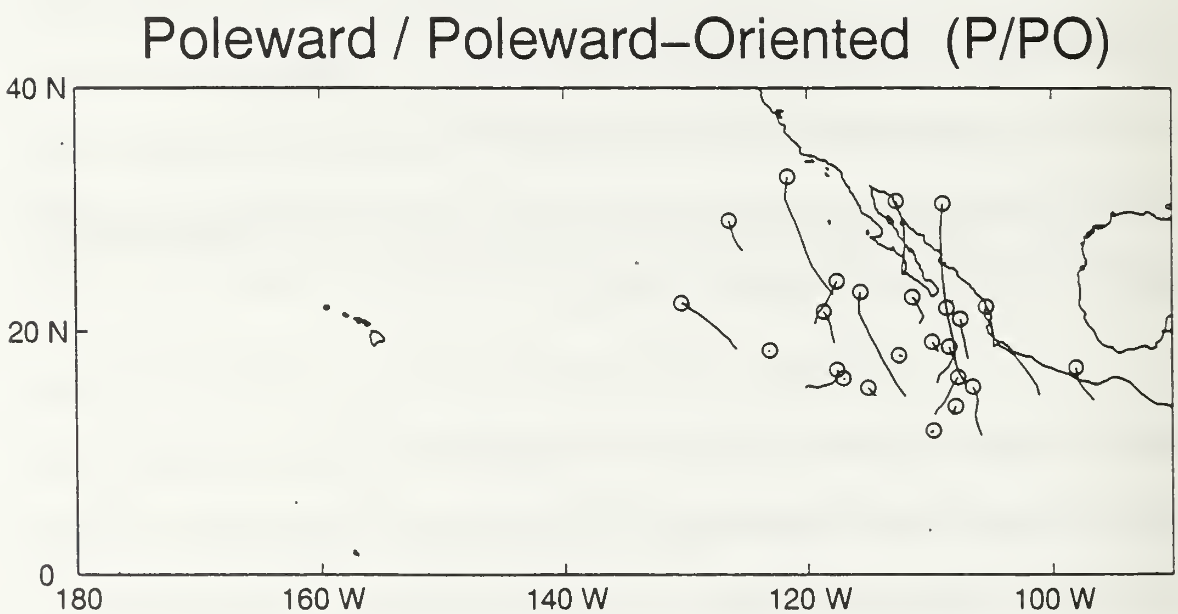


Figure 25. Tracks as in Fig. 1, except only while TC was in the Poleward (P) pattern and Poleward-Oriented (PO) region.

c. *Low Pattern*

(1) Conceptual model. Another change to the environment structure knowledge base (Fig. 14, upper left) is the new Low (L) pattern conceptual model in the ECPac (Fig. 26). The WPac monsoon gyres are large-scale patterns associated with the Asian monsoon reinforced by the warming of the lower troposphere via sensible and latent heat fluxes above a large warm pool of ocean water. Such phenomena do not occur over the ECPac in association with the North American monsoon, and coastal upwelling and equatorward transport of cold polar water would be unfavorable. Although monsoon gyres were not found in ECPac during this 7-year period, mid-level lows with midlatitude origins have similar effects.

Upper-level lows in the midlatitude wave train often become cutoff in ECPac and drift southwestward into lower latitudes where they may come close to a TC. If the TC and upper-level low come into contact soon after the low has cutoff, then the strong westerly winds on the south side impose a vertical wind shear that may disperse the warm core of the TC. If the low has been cutoff for a few days and cyclonic momentum extends downward at least to the mid-levels, less vertical shear may be imposed on an adjacent TC. This region may then have a TC-environment structure similar to the G/PO pattern/region of WPac (Fig. 4c). This environmental flow tends to advect the TC poleward and cyclonically about the low center.

Although the L pattern conceptual model (Fig. 26) is similar to that of the G pattern (Fig. 4c), some differences are noted. First, because they form from

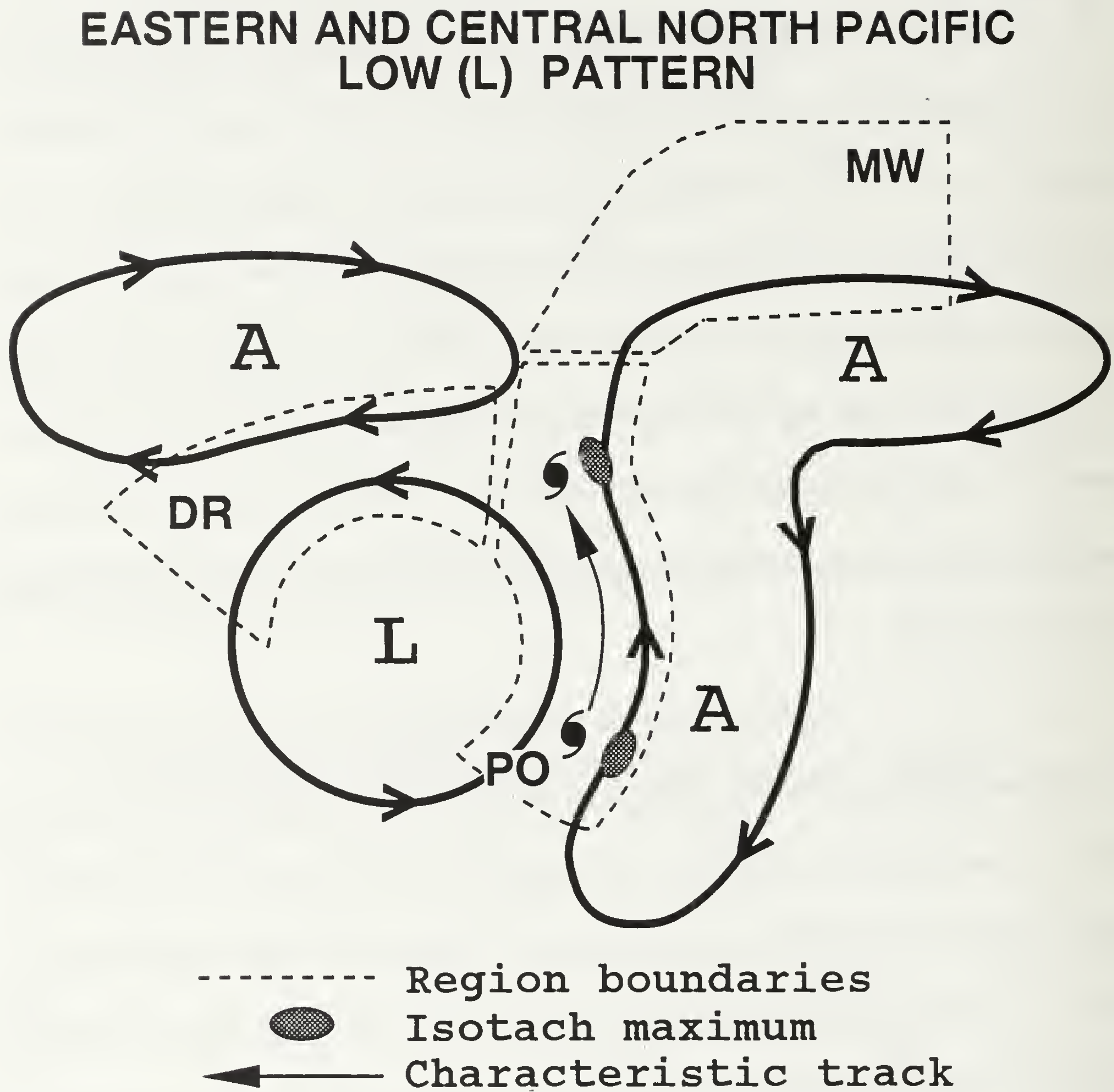


Figure 26. Conceptual model as in Fig. 16, except for Low (L) synoptic pattern and Poleward-Oriented (PO), Dominant Ridge (DR), and Midlatitude Westerlies (MW) synoptic regions. None of the TCs in the 7-y sample was observed in the DR or MW synoptic regions.

different causes and are at different levels, lows in the EastPac have a different appearance in the satellite imagery than the WPac gyres. The key satellite signature of a gyre is a large ring of moderate convection surrounding a relatively cloud-free area. Satellite interpretation is critical in identifying gyres because numerical analyses often do not depict well the wind flow or slight pressure signature of the low-level feature. In the satellite imagery, an ECPac cutoff low, which has developed down enough to destabilize the near-surface inversion, typically has deep convection in the center, a relatively clear surrounding area, and often a band of clouds will be aligned along a weakening baroclinic zone to the east (Fig. 19b, upper left). A second difference is that ECPac TCs move poleward over cooler water and tend to dissipate at lower latitudes than WPac TCs. Hence, TCs in this seven-year sample were never observed to survive long enough to be advected cyclonically to the Dominant Ridge (DR) region on the northwest side of the low, or farther poleward into the MW region (Fig. 26).

(2) Analysis example. Hurricane Adrian at 00 UTC 17 June 1993 (Fig. 27) is an example of a TC moving poleward in the L/PO pattern/region. The mid-level low near 22°N, 131°W had previously cutoff from the midlatitude westerlies and drifted southward. Much as in the L pattern conceptual model (Fig. 26), the NOGAPS analysis depicts the cutoff low surrounded by the STA to the north and a strong peripheral anticyclone to the east and southeast. Although the TC translation speed is now only 4 kt, the southerly flow between the low and the peripheral anticyclone had been advecting Adrian poleward at 7 kt during the previous day. Notice how the 20-kt isotach maximum

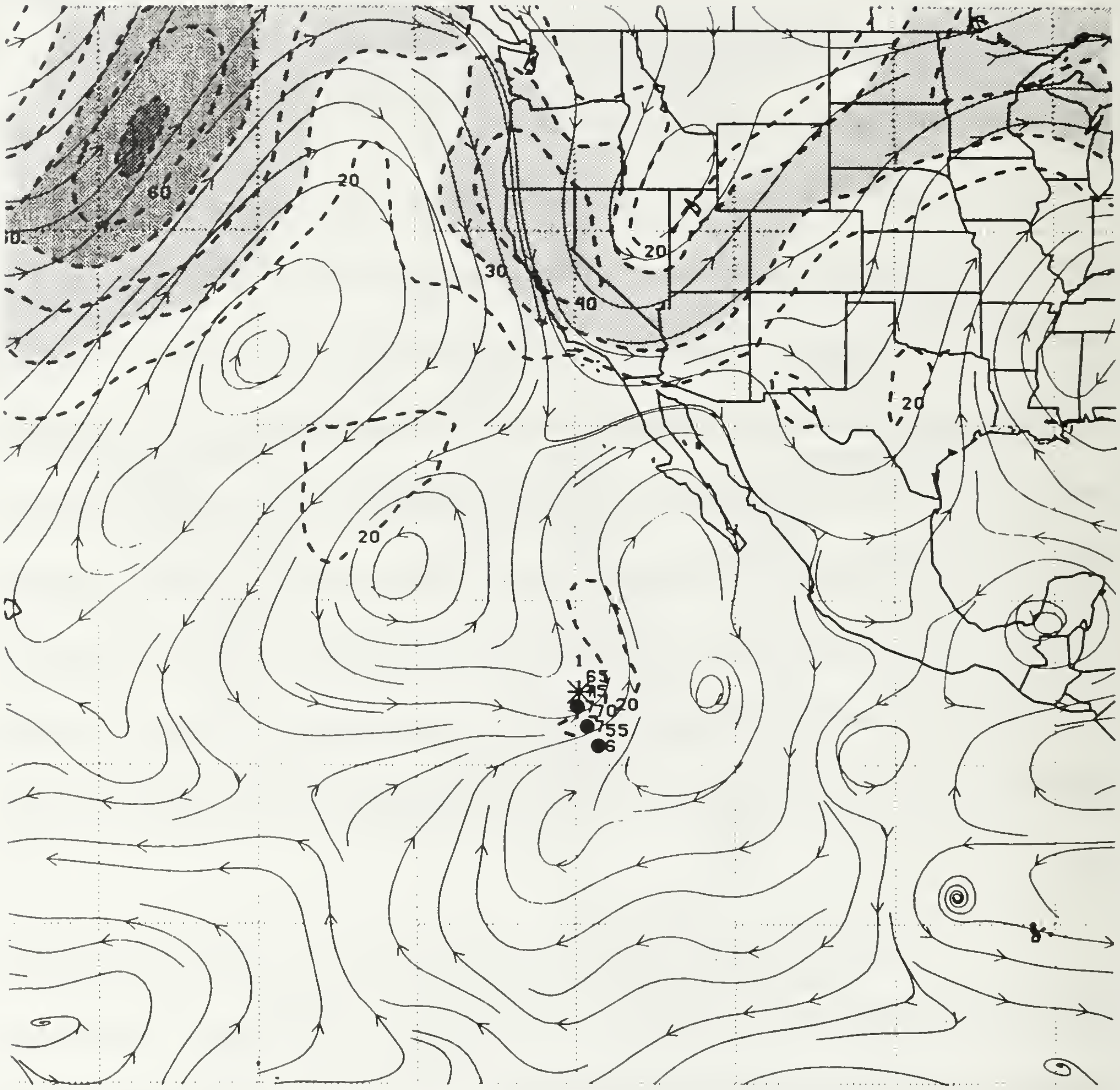


Figure 27. NOGAPS 500-mb analysis as in Fig. 17, except it illustrates an L/PO case at 00 UTC 17 June 1993 (Hurricane Adrian).

extends from the east side all the way to the southwest of the TC center, which is indicative of the TC poleward motion caused by the strong peripheral anticyclone.

(3) Tracks. The tracks of TCs in the L/PO pattern/region (recall that no L/DR or L/MW cases were found) occur over a large portion of the domain, but with a cluster around 20°N between 120°W and 130°W (Fig. 28). Mid-level lows, much like the troughs that help create the S/WR pattern/region, may become cut off anywhere along the STA axis. The length of the track is highly dependent upon the strength, depth, and persistence of the low. If a low is strong and long-lasting, then perhaps the TC can be advected for a long time, which was the case of Hurricane Iniki, whose track in Fig. 28 runs poleward along 160°W. If a low loses its vertical structure, then a TC may soon be sheared apart. The directions of L/PO tracks also possess a perceptible amount of variabililty in direction, which is attributed to the variations of strength, orientation, and motion of the lows. However, the overall sample of L/PO tracks exhibit a general poleward motion.

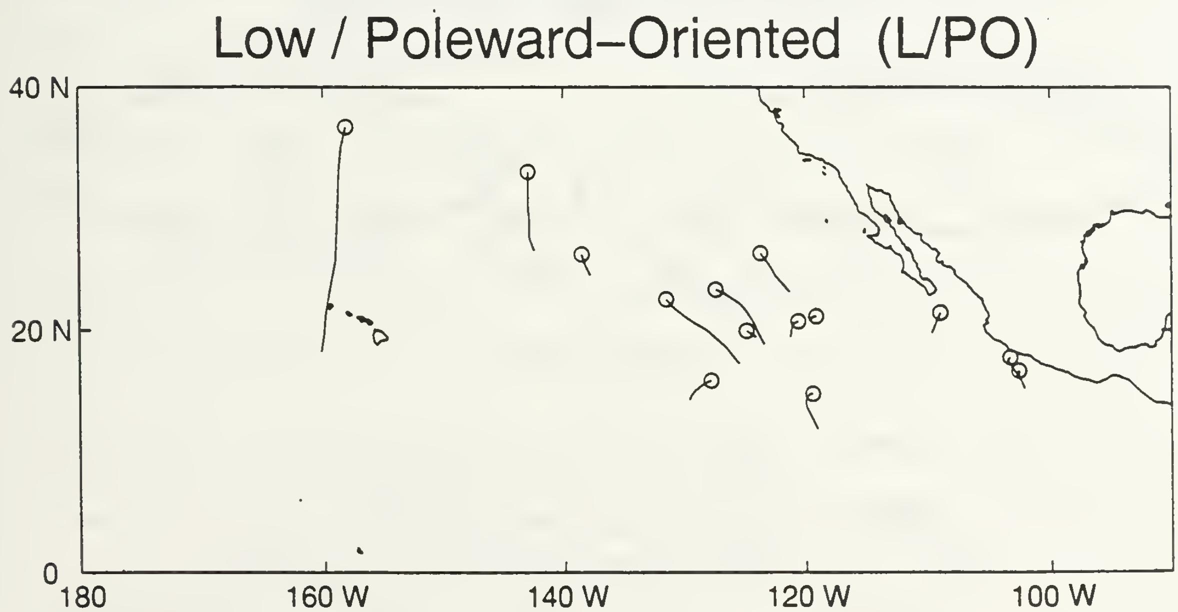


Figure 28. Tracks as in Fig. 1, except only while the TCs were in the Low (L) pattern and Poleward-Oriented (PO) region.

d. Multiple Pattern

(1) Conceptual model. The ECPac Multiple (M) synoptic pattern conceptual model (Fig. 29) is exactly the same as that of the WPac (Fig. 4d). The important determining factors for both the EF and PF regions of the M pattern are whether or not the TC is roughly 10°-20° latitude from another TC and the TC be located in the increased pressure gradient area between the STA and the other TC. The TCs in the Equatorward Flow (EF) synoptic region usually move slowly to the southwest (short track arrow), while TCs in the Poleward Flow (PF) region move quickly to the northwest (long track arrow). However, the zonally-oriented STA in the schematic must be taken as just a rough indicator of the orientation of the STA in the ECPac, which is known to be bowed rather than zonal.

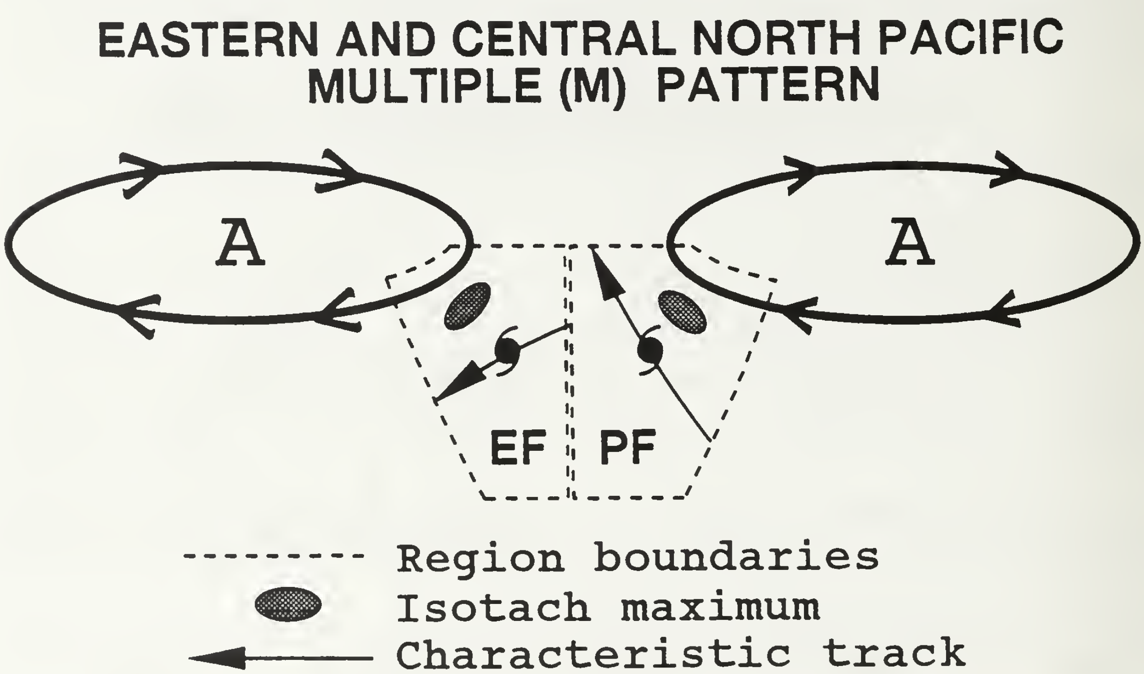


Figure 29. Conceptual model as in Fig. 16, except for Multiple (M) synoptic pattern and Equtorward Flow (EF) and Poleward Flow (PF) synoptic regions.

As previously mentioned for the WPac M pattern, the western TC often goes into M/EF before the approaching eastern TC moves farther north and eventually into the M/PF pattern/region. This lag time is increased even more in the ECPac owing to the northeast-southwest tilt of the STA over the eastern North Pacific Ocean. The eastern portion of the STA, which eventually helps advect the eastern TC, is farther north because of this tilt, and the TC must first travel the extra distance northward before entering the M/PF pattern/region.

(2) Analysis example. The case of Hurricane Olivia and TD 18E (soon to be TS Paul) during 1994 is an example in which both TCs are simultaneously in the M pattern. GOES infrared imagery at 05 UTC 25 September 1994 (Fig. 30a) shows the smaller TD 18E near 14°N, 130°W and the larger Hurricane Olivia to the east at about 18°N, 120°W. Although the TCs are close to each other, they are separated too far to be undergoing a Direct TC Interaction (DTI). Rather, this is a Semi-direct TC Interaction (STI), which typically requires a separation distance of greater than 10° latitude as in this situation. The clear area between the two TCs on the GOES imagery (Fig. 30a) is indicative of two distinct circulations. The NOGAPS analysis seven hours later (Fig. 30b) depicts the typical, tilted STA over the Pacific Ocean, although it is about 10° latitude farther south than normal. TD 18E, which is located in the M/EF pattern/region between the STA cell to the west and Olivia to the east-northeast, is tracking to the west-southwest at a slow 4 kt. Thus, Olivia, in conjunction with the western STA cell, has established an equatorward pressure gradient and hence equatorward flow over TD 18E as in the conceptual model (Fig. 29). On

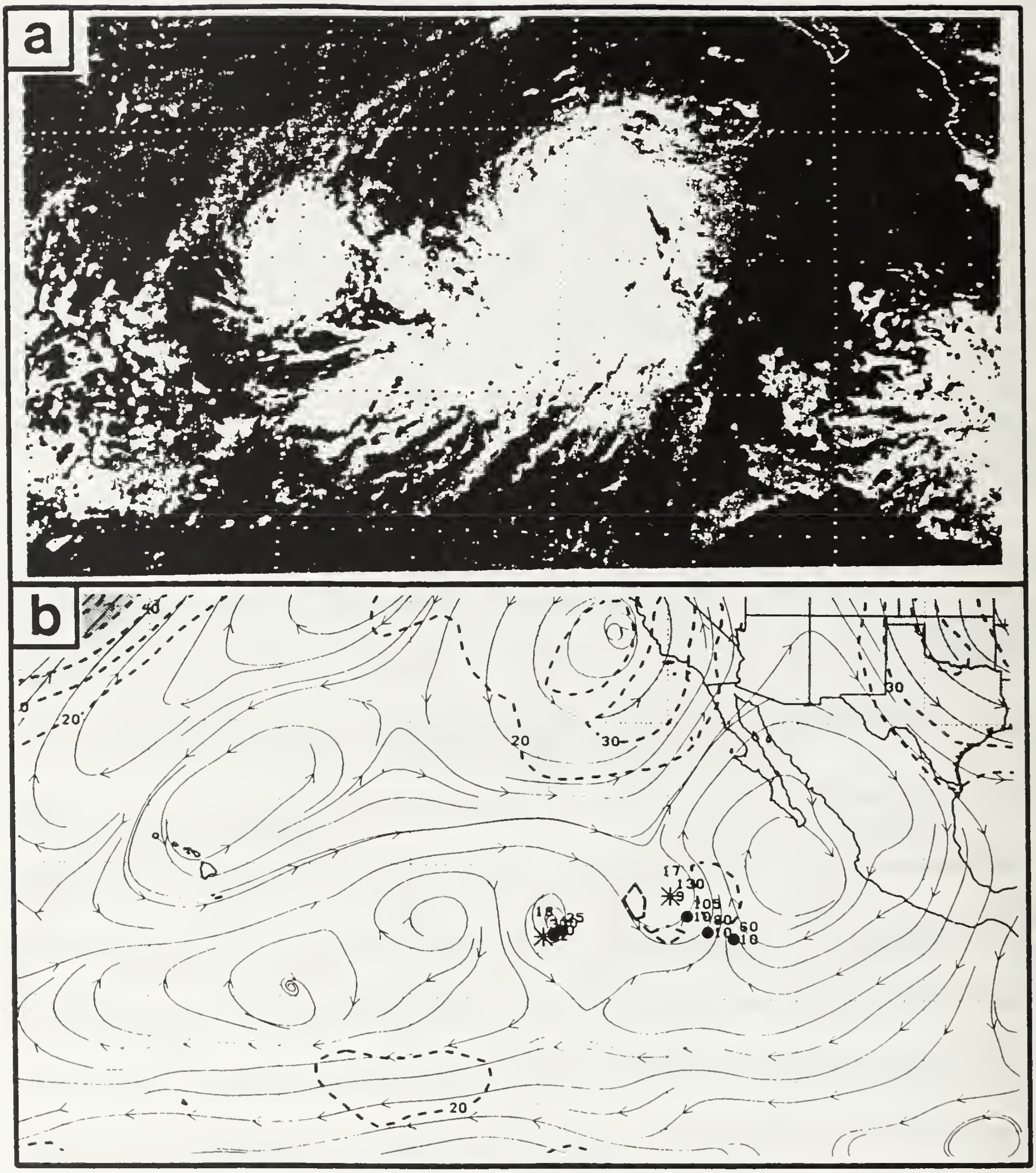


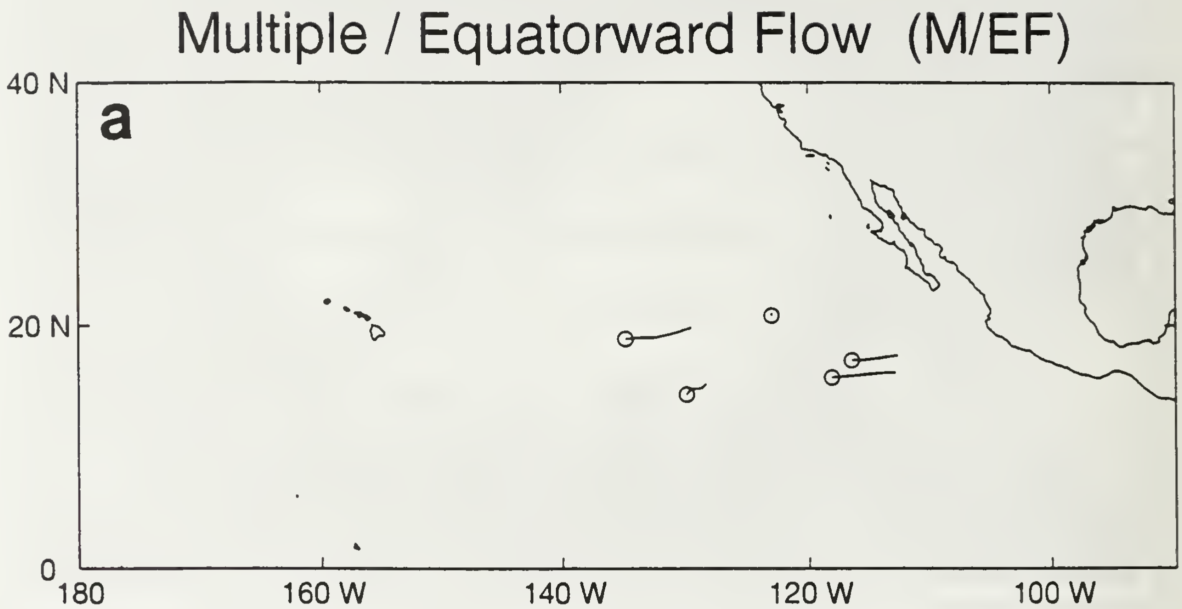
Figure 30. (a) GOES infrared imagery at 05 UTC 25 September 1994. (b) NOGAPS 500-mb analysis as in Fig. 17, except it illustrates a M pattern case at 12 UTC 25 September 1994 (TD 18E is TC #18 to the west and Hurricane Olivia is TC #17 to the east).

the other hand, Olivia is moving quickly to the northwest at 9 kt in the corresponding M/PF pattern/region. That is, TD 18E is helping to increase the pressure gradient and poleward flow over Olivia above that which might be expected if Olivia was simply moving through a S/WR pattern/region. Notice that although 20-kt isotach maxima are present on three sides of Olivia, the largest one is to the east, as expected.

(3) Tracks. The tracks of five TCs during 1990-96 that are in either the EF and PF synoptic regions of the M pattern are shown in Fig. 31a, b, respectively. The tracks in the EF region are all directed toward the west-southwest while the PF tracks are toward the northwest. Once in the M pattern, the western TC generally moves slowly equatorward, while the eastern TC moves quickly poleward. Thus, the separation distance between the two TCs soon increases and the M pattern then breaks down. Hence, the tracks in both regions are relatively short owing to the self-limiting nature of the M pattern. Notice that few TCs in the M pattern during this 7-y period are limited to a small region in the center of the eastern North Pacific domain. The orientation of the ECPac STA and the larger number of TC formations in that small area compared with the rest of the domain are suggested as the reasons for this confined distribution.

3. Climatology

A climatology of the environment structure characteristics provides forecasters an idea of the frequency of each synoptic pattern/region combination. Every 00 and 12 UTC date-time group (DTG) for which a NOGAPS analysis is available is counted as a single unit for each TC. A total of 135 TCs resulted in 1858 DTGs in this 7-y sample (see Appendix).



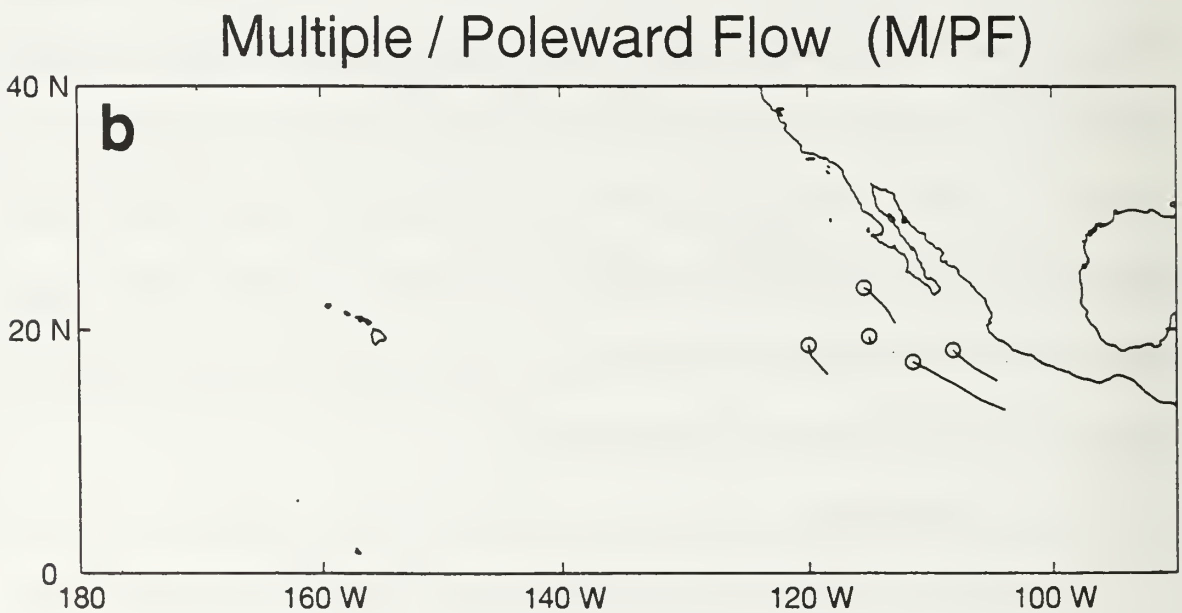


Figure 31. Tracks as in Fig. 1, except only while the TCs were in the Multiple (M) pattern and (a) Equatorward Flow (EF) or (b) Poleward Flow (PF) regions.

The record of Hurricane Ilena of 1994 (Table 1) provides an accurate description of the track and environment structure of the TC as well as an example of the climatology methodology. Best-track data describe the position, translation speed, and intensity every 6 h, while the environment classification is every 12 h when a NOGAPS analysis is available. Ilena formed at 12 UTC 10 August 1994 in the S/RP synoptic pattern/region. Thirty-six hours later, the formation of TD 12E nearby started the process of changing the environment of Ilena into the M/PF synoptic pattern/region via the STIE transitional mechanism. Whereas a transition into the M pattern seemed likely for 36 h (see dual pattern/region classifications in Table 1 beginning 00 UTC 12 August), TD 12E was just too small to affect Ilena enough to completely change the environment structure. By 12 UTC

TC	DATE	HR	LAT	LONG	DIR	SPD	INT	SIZ	PATT	REG	TRANS	REMARKS
11	940810	12	14.5N	107.5W	***	***	25		S/	RP/		Isotach SE
11	940810	18	15.0N	107.5W	360	5	25		/	/		by small AC
11	940811	00	15.6N	107.5W	360	6	25		S/	RP/		Isotach E
11	940811	06	16.2N	107.6W	350	6	30		/	/		
11	940811	12	16.7N	107.9W	330	6	35		S/	RP/		Isotach ENE
11	940811	18	17.3N	108.3W	327	7	45		/	/		
11	940812	00	18.0N	108.9W	320	9	50		S/M	RP/PF	STIE	TD12 forms
11	940812	06	18.8N	109.5W	324	10	55		/	/		to WSW
11	940812	12	19.8N	110.3W	322	13	60		S/M	RP/PF	STIE	TD12 small;
11	940812	18	21.0N	111.2W	324	15	65		/	/		not M/PF yet
11	940813	00	22.4N	112.2W	326	17	65		S/M	RP/PF	STIE	
11	940813	06	23.7N	113.4W	319	17	60		/	/		
11	940813	12	24.8N	114.7W	312	16	55		S/S	RP/RE	ADV	Isotach NE
11	940813	18	25.6N	116.3W	298	17	50		/	/		
11	940814	00	26.3N	118.0W	294	17	40		S/	RE/	ADV	Isotach NNE
11	940814	06	26.7N	119.8W	283	17	30		/	/		
11	940814	12	26.9N	121.7W	276	17	25		S/	RE/		
11	940814	18	27.0N	123.5W	273	16	25		/	/		

Table 1. Systematic Approach record for Hurricane Ilena of 1994. The columns are TC number, date (YYMMDD), hour, latitude, longitude, direction, translation speed (kt), intensity (kt), size (not recorded), synoptic pattern, synoptic region, transitional mechanism, and remarks. Direction and translation speed are determined from the previous 6 h motion. Primary pattern and region classifications are left of the slash, while secondary patterns and regions indicating a possible transition are right of the slash.

13 August, Ilena has moved westward enough to begin a transition into the S/RE pattern/region by simple advection (ADV in transformation column of Table 1). This transition is completed by the next NOGAPS analysis, and Ilena remains in S/RE until it dissipates late on 14 August. For the purpose of this climatology, each dual pattern/region is given a "credit" of one half to each combination. Thus, the final tally for the pattern/region combinations of Ilena are 5 DTGs in S/RP, 1.5 in M/PF, and 2.5 in S/RE. However, only one transition from S/RP to S/RE was actually completed.

The frequency of TCs in each of the synoptic pattern/region combinations is shown in Fig. 32. The S pattern is by far the most common pattern at 87%, which is substantially higher than the 60% of WPac. The two synoptic regions equatorward of the STA axis, namely RP and RE, comprise much of the data set with frequencies of 28% and 47%, respectively. Also, the 9% count for the S/WR pattern/region in ECPac is higher than that for the S/WR of WPac, which is caused by more midlatitude troughs breaking the weaker STA in the ECPac and establishing a poleward steering flow. Finally, the S/MW pattern/region occurs infrequently (3%) because TCs are often being sheared apart or dissipated over low SSTs just as they enter the midlatitude westerlies.

The other three ECPac synoptic patterns occur much less frequently than the S pattern. However, the M pattern (3%) occurs just as frequently in ECPac as it does in WPac. Although this may seem surprising, ECPac TCs form in a much smaller domain so that just as frequently TCs can come within the 10°-20° latitude separation distance and affect the other track. The smaller sizes of TCs in the TCPac is the key factor for the low frequency

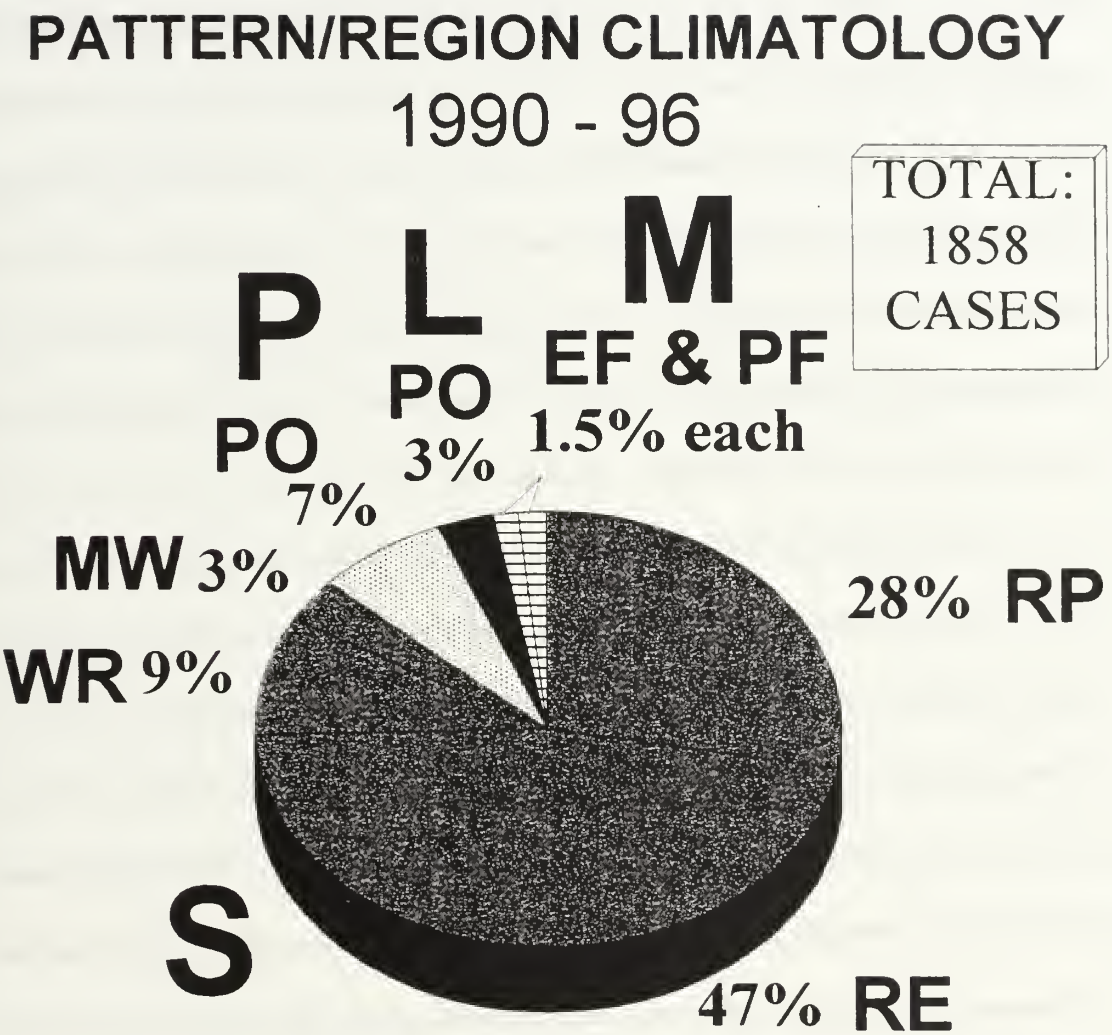


Figure 32. Climatology (percent) of synoptic pattern/regions in the ECPac environment structure for 1858 cases during 1990-96, with patterns separated by shading: S (grey), P (speckled), L (black), and M (lines).

of the P pattern (7%), which is much less than the 30% of WPac. A smaller TC can not build as strong a peripheral anticyclone via Rossby wave dispersion, and thus is less likely to establish a poleward steering current. Finally, the L pattern (3%) occurs less frequently than the WPac counterpart G pattern (7%). On average, five TCs a year are affected by a WPac monsoon gyre while less than three TCs are advected poleward by ECPac mid-tropospheric lows. Part of the reason for this higher number in WPac is because TCs may be present all around the G pattern in three synoptic regions (Fig. 4c), while ECPac TCs only remain intact in the PO region of the L pattern.

In this 7-y sample, TCs are found in only eight of the possible 11 synoptic regions in four synoptic patterns in the ECPac. Thus, less environmental structure options appear to exist in the ECPac than the ten synoptic pattern/region combinations in the WPac. The dominance of the S/RP and S/RE combinations is not surprising in terms of the track distribution in Fig. 22a,b, with 75% of all classifications in either of these slightly north or slightly south of west tracks, respectively. Except for the 1.5% of M/EF classifications, all of the remainder of the pattern/region combinations involve poleward tracks. However, these represent only about 23.5% of all classifications.

C. TRANSITIONS AND TRANSITIONAL MECHANISMS

Properly defining the current synoptic environment is a crucial step in understanding the current and perhaps near-future motion of a TC. The consistent tracks of TCs within each synoptic pattern/region (Figs. 22, 25, 28, and 31) suggest that simply knowing the

current synoptic pattern/region classification helps narrow the possible track directions. If a forecaster knows that the current situation will be persistent, then he/she can confidently provide a track forecast similiar to those in the track plots for the given synoptic pattern/region combination. In general, track forecasts tend to be less difficult when the track direction and speed are persistent, i.e., when the present environment structure is not likely to change during the forecast period. By contrast, the largest forecast errors tend to occur when the track changes, i.e., when the environment structure changes. Describing the environment with the Systematic Approach concepts of environment structure classification and transitional mechanisms should provide insight into the likelihood and physical causes of how the environment is changing and the subsequent effect on TC tracks.

1. Transition Climatology

The transition climatology for the 7-y sample provides the number of completed "recurring" transitions from one synoptic pattern/region to another (Fig. 33). Recurring means that the type of transition occurred more than once during the seven years. The 135 TCs experienced a total of 245 transitions, which means that a typical TC will experience about two transitions, and during these transitions the TC track may be expected to be more difficult to forecast. However, ten of these transitions were of a rare type that occurred only once, which leaves 235 recurring transitions. Twenty-one TCs remained in the synoptic pattern/region in which they formed for their entire lives. Most of these persistent TCs were in the S/RE (12) and S/RP (8) synoptic pattern/regions, although one did remain in P/PO all of its life.

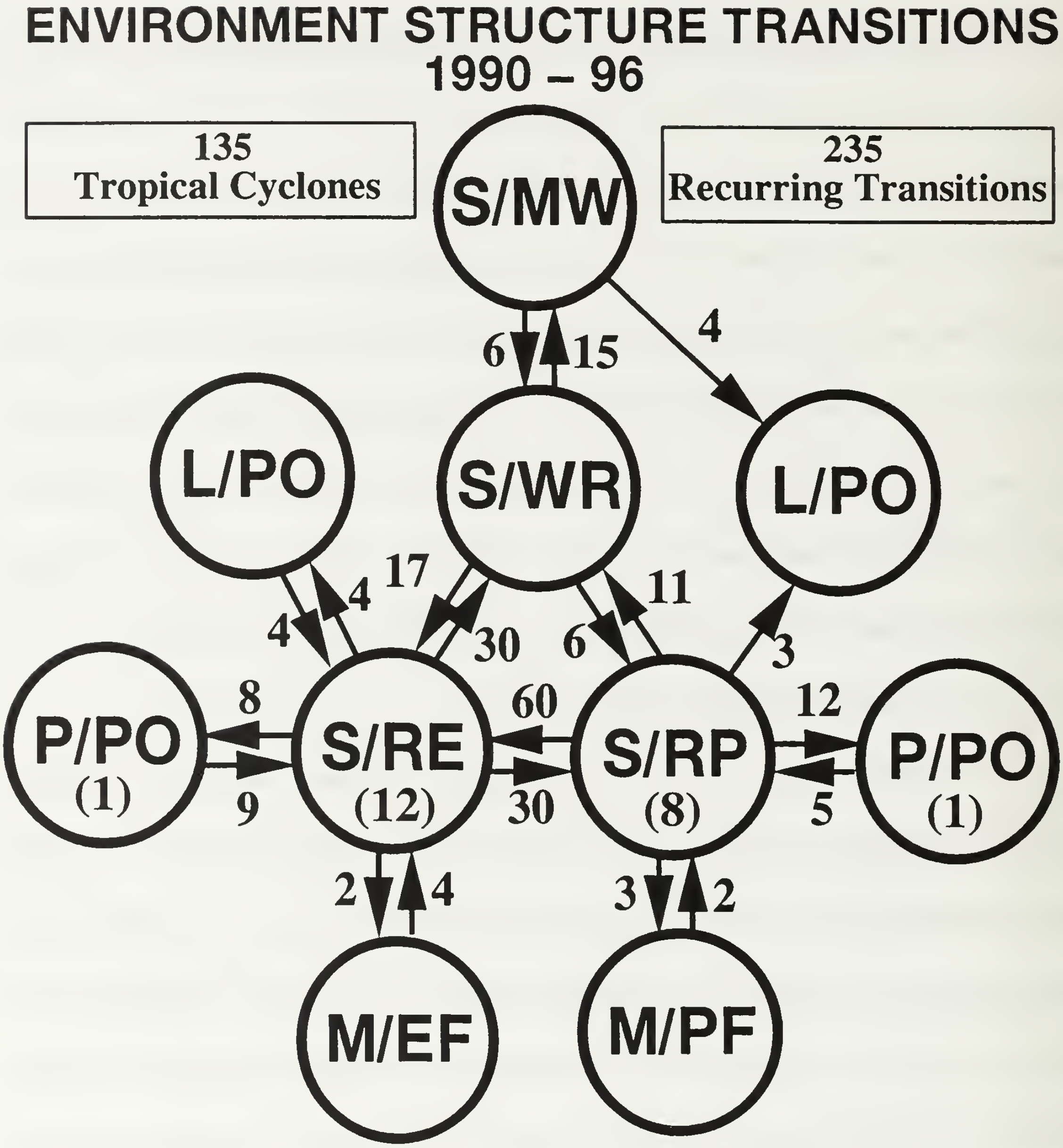


Figure 33. Environment structure transition occurrences for the 135 TCs in ECPac during 1990-96. Only "recurring" transitions that occurred more than once during the period are included, with a total of 235 recurring transitions. Numbers in parentheses within a pattern/region marker indicate the number of TCs that persisted in that environment structure for their entire lives. The P/PO and L/PO combinations are repeated only to make the diagram more visually appealing.

Not surprisingly, most transitions (Fig. 33) occur between the four synoptic regions of the S pattern, which is the most prevalent pattern (Fig. 32). The most common transition is from S/RP to S/RE (60), which is expected owing to the large number of ECPac straight-running TCs that move westward while equatorward of the STA in the S pattern. That is, many TCs that form south of Central America are first in the S/RP pattern/region and later are advected into the S/RE combination, which is labelled as a transition. The other common transitions occur less than half as often as the first one (Fig. 33). TCs moved into the Weakened Ridge (WR) region of the S pattern from the S/RE 30 times, which is almost three times as common as the number of times TCs made the same transition from the S/RP (11). Thirty S/RE to S/RP transitions were also observed. In some of these cases, the TCs moved far to the west and came under the influence of the Central Pacific anticyclone. In other cases, the SRM processes changed the orientation of the STA to change the environmental flow from northeasterlies to southeasterlies.

An important aspect of the transition climatology (Fig. 33) is that transitions that lead to TC tracks turning poleward are more frequent than equatorward transitions. For instance, S/RE to S/WR occurred 30 times, while the opposite only took place 17 times. The S/WR to S/MW transition happened 15 times, and a return from the westerlies was recorded only six times. Although ECPac tends to have more westward straight-running TCs than other basins, ECPac TCs eventually move poleward and dissipate at a latitude greater than that at which they form.

2. Case studies

The following case studies provide examples of the common transitions, as well as the transitional mechanisms that help explain the physical reason for the environment structure change. The most common transitional mechanisms are presented, along with the new and/or modified ones that are required to complete the ECPac knowledge base (Fig. 14).

a. S/RP to P/PO to S/RP to S/RE (Hurricane Henriette 1995)

Hurricane Henriette was one of the relatively few ECPac TCs that was able to modify its environment enough to complete a transition from the S pattern to the P pattern. However, the strong STA remained, and Henriette eventually returned so that a P/PO to S/RP transition also occurred. Thus, Henriette made two substantial turns followed by a more subtle one during its life (Fig. 34).

At 12 UTC 1 September 1995 (Fig. 35a), the typical bowed STA is centered near 37°N, 108°W over southwestern U.S. and extends to the southeast over Cuba and southwest to just south of Hawaii. Because Henriette is just slightly east of the longitude of the STA apex, the environment is considered to be in the S/RP combination, although the TC seems close to the northeasterlies of the S/RE pattern/region. However, a peripheral anticyclone that is characteristic of the P pattern is building via the TC-environment transitional mechanism called RMT (Fig. 14, lower right) to the southeast of Henriette. Clear skies southwest of the Gulf of Tehuantepec on GOES infrared imagery at 1130 UTC (Fig. 35b) substantiate the presence of the peripheral anticyclone in the NOGAPS analysis.

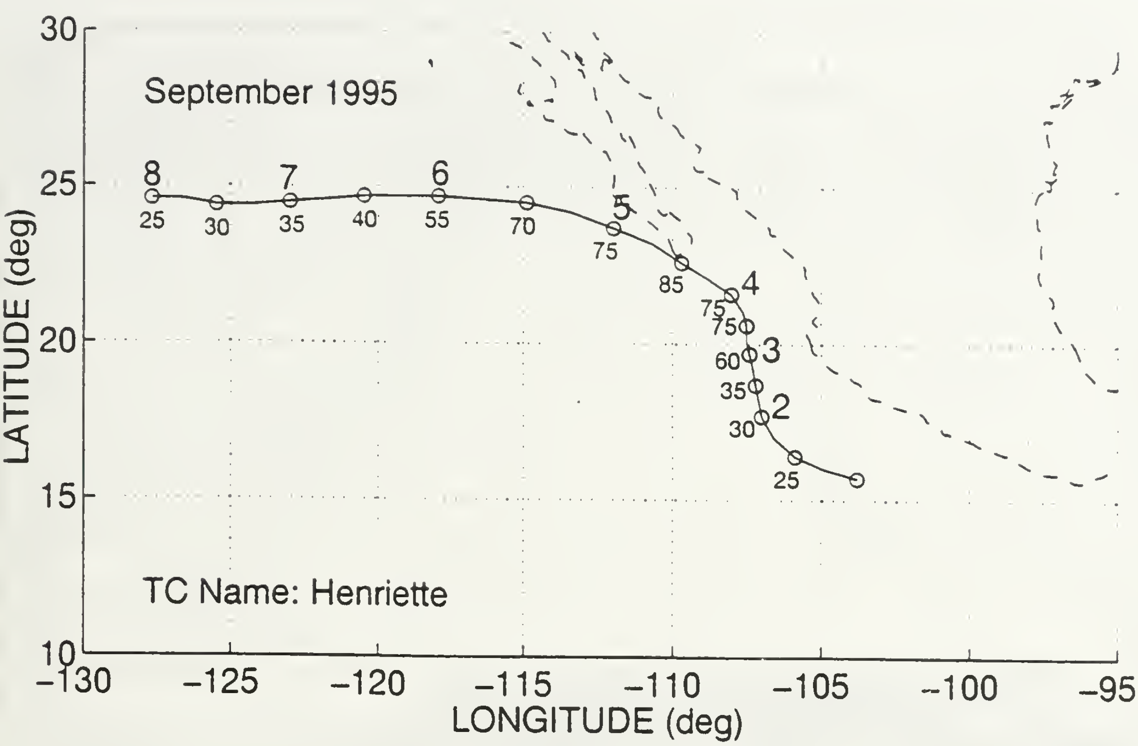


Figure 34. A portion of the Hurricane Henriette best track in September 1995. The best track is a solid line with circles indicating every 00 and 12 UTC position. Large bold numbers are the date next to the 00 UTC position. Small numbers are the intensity every 12 h. The coastline is dashed.

A 20-kt isotach maximum is already analyzed southeast of the TC, and Henriette is slowly beginning to turn northward (Fig. 34). Hence, the environment is in a transitional state from S/RP to P/PO.

Twenty-four hours later (Fig. 35c), the peripheral anticyclone has grown larger, and Henriette is tracking poleward in the P/PO pattern region. The TC translation speed has slowed slightly, which helps explain the temporary disappearance of the isotach maximum to the southeast that was present in Fig. 35a. Notice that although Henriette is currently in the P pattern, the STA still remains strong to the north. This just completed

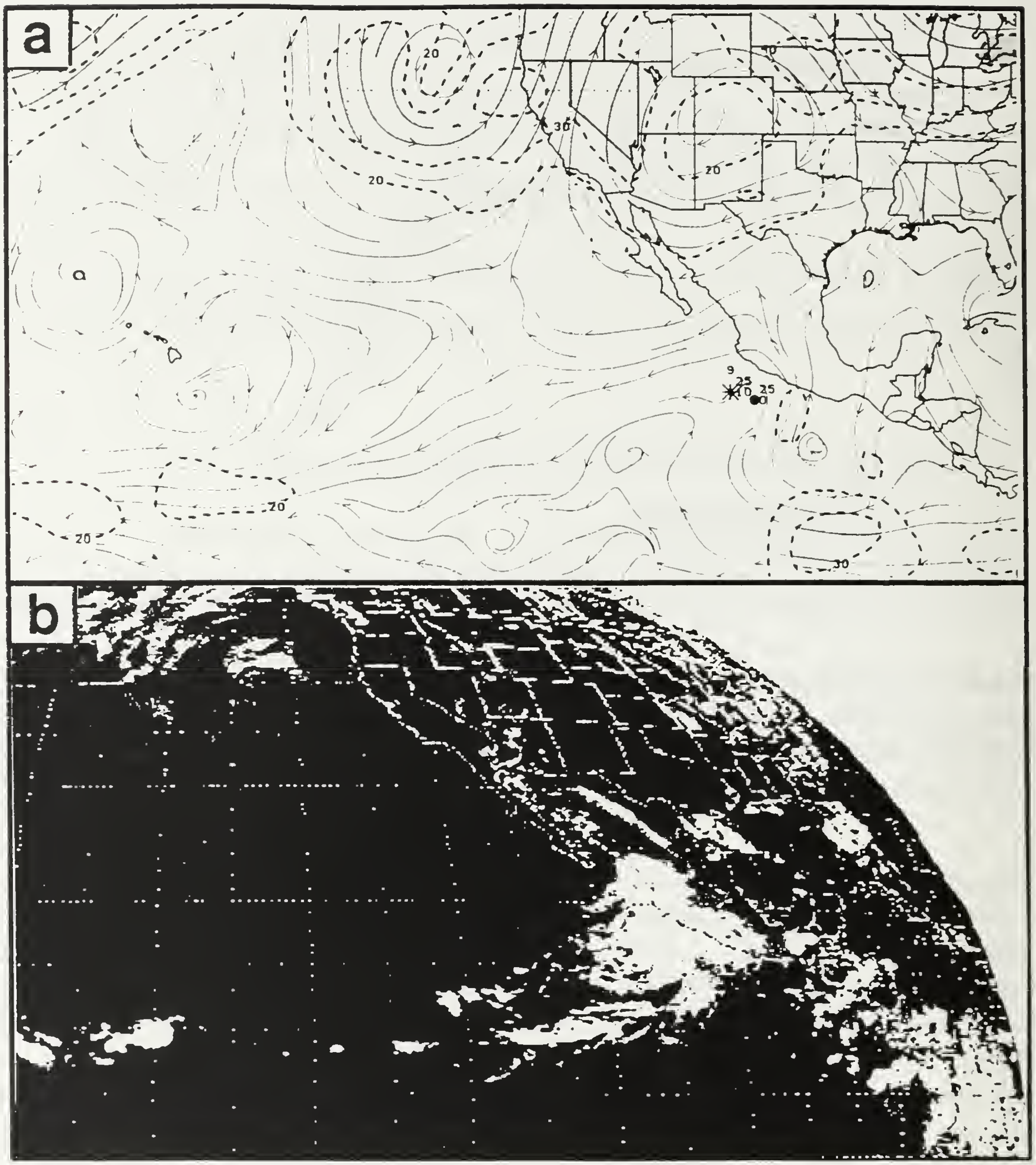


Figure 35. (a) NOGAPS 500-mb analysis as in Fig. 17, except at 12 UTC 1 September 1995. (b) GOES infrared imagery at 1130 UTC 1 September 1995.

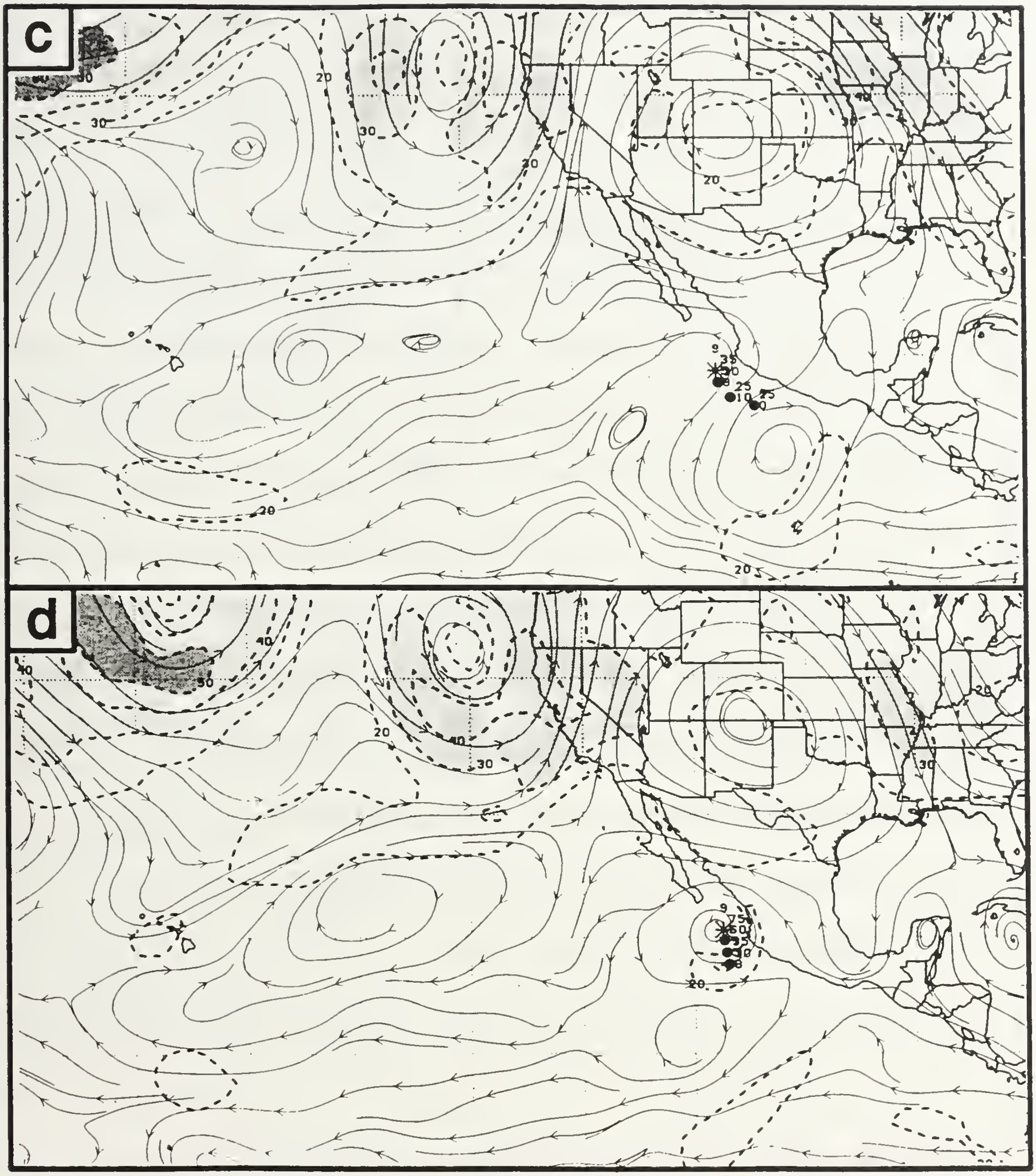


Figure 35. (continued) Like (a), except at 12 UTC (c) 2 and (d) 3 September 1995.

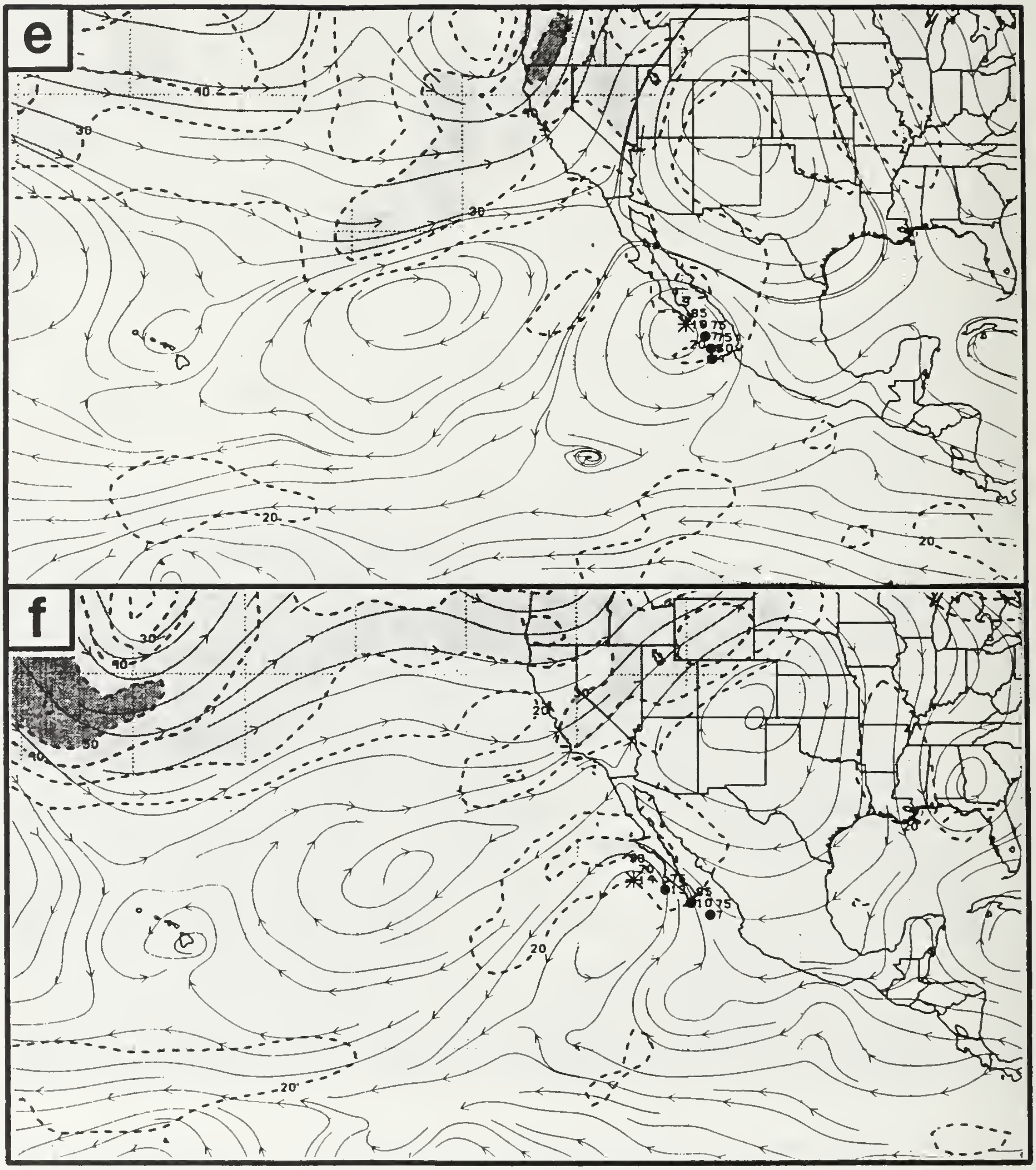


Figure 35. (continued) Like (a), except at 12 UTC (e) 4 and (f) 5 September 1995.

transition to the P/PO pattern/region from S/RP, which occurred twelve times during the 7-y sample (Fig. 33), is more common than the similar transition from S/RE, which happened eight times. The orientation of the STA in Fig. 35c helps explain this difference in frequency. When a TC is in the eastern S/RP pattern/region, the eastern branch of the STA is tilted from northwest to southeast, which is toward the eastern side of the TC where a peripheral anticyclone is expected to develop. This growing peripheral anticyclone can easily attach to the relatively close STA to the northeast and modify the TC environment. When a TC is in the S/RE pattern/region, the western branch of the STA is tilted from southwest to northeast, which means that the STA is farther from a peripheral anticyclone building to the southeast of the TC. Thus, a larger TC with more Rossby wave dispersion is required for a S/RE to P/PO transition than for a S/RP to P/PO transition.

By 3 September (Fig. 35d), Henriette is still tracking poleward (Fig. 34) in the P/PO pattern/region. As often happens in the ECPac, the peripheral anticyclone is quickly dissipating. Consequently, the smaller peripheral anticyclone detaches from the STA and moves west. A 30-kt isotach is now located to the south between Henriette and the dying anticyclone. No transitional mechanism is considered to be happening and the P pattern just dissipates.

After another 24 h (Fig. 35e), no indications of the peripheral anticyclone exist, and the TC is back in the S/RP pattern/region. Henriette has finished the second major turn and is moving to the northwest (Fig. 34), as is also indicated by the position of the maximum isotach to the northeast. Although the TC is west of the STA apex, which is now

over Colorado, Henriette is not yet in the RE region because it is still on the southwest side of the continental STA, and is embedded in southeasterlies that are advecting the TC to the northwest.

One day later (Fig. 35f), the STA structure has changed very little, but Henriette has made the most common transition from the southeasterlies of the RP region to the northeasterlies of the RE region. The 30-kt isotach is now north of the TC. Advection of Henriette by environmental flow from one region to another within the S pattern is the only transitional mechanism acting to change the TC environment (Fig. 14, lower left). Henriette then moves westward in the S/RE pattern/region for the next several days until it dissipates on 8 September (Fig. 34).

b. S/RE to S/RP via ADV (Hurricane John 1994)

The transition from the S/RE to S/RP pattern/region, in which a TC remains in the trade wind easterlies equatorward of the STA axis in the S pattern, is one of the second most common transitions (Fig. 33). There are two main ways in which this transition can occur. As previously discussed in this chapter, Hurricane John of 1994 experienced this transition via advection (ADV) by environmental flow (Fig. 14, lower left) as the TC moved from the eastern Pacific northeasterlies (Fig. 19c) into the southeasterlies on the southwest flank of the central Pacific anticyclone (Fig. 19d). The effect on the track of John is a turn from southwestward to northwestward (Fig. 36). John remained in the central Pacific S/RP pattern/region and continued to move northwestward until it crossed the dateline.

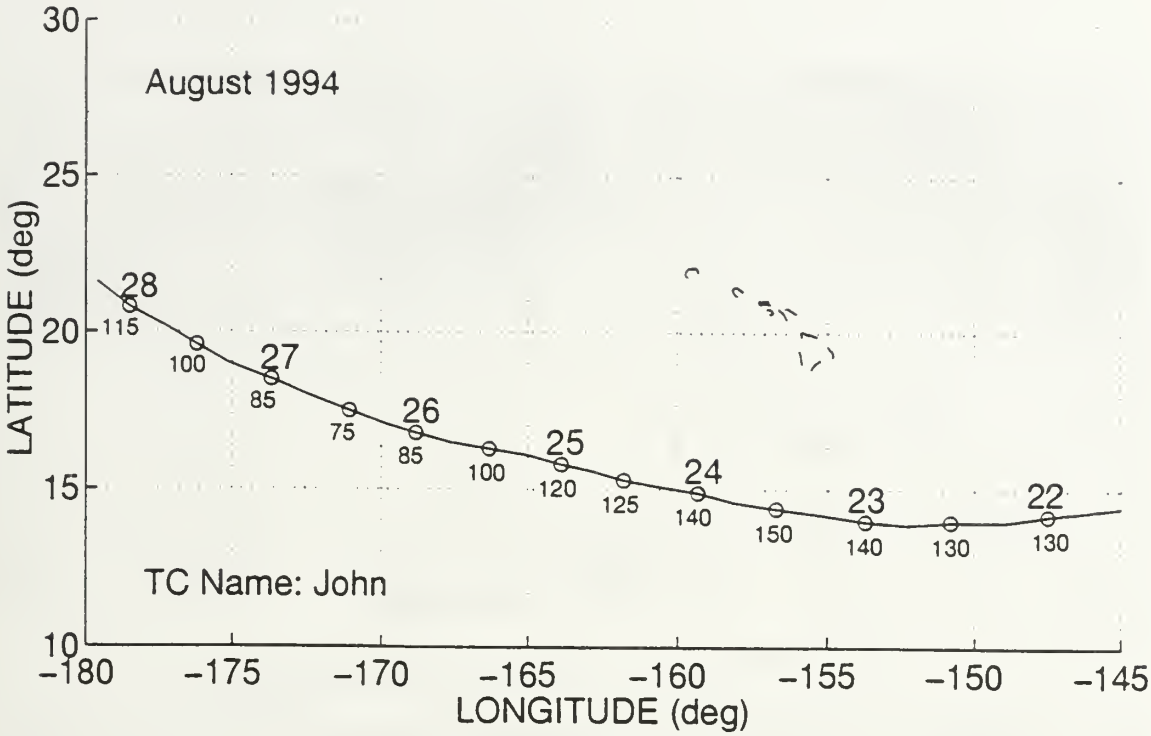


Figure 36. Best track, as in Fig. 34, except for Hurricane John in August 1994.

c. *S/RE to S/RP via SRM (TD 01E 1996)*

The second way that a TC may complete a transition from the S/RE to the S/RP pattern/region is more complicated than by simple advection. In the case of TD 01E of 1996, the STA is modulated via the SRM process. When TD 01E forms at 12 UTC 13 May 1996, it is moving slightly north of west (Fig. 37) in the northeasterlies of the S/RE pattern/region to the south of a bowed STA (Fig. 38a). Although the STA is oriented as expected, it is only May, and the STA is not as strong as in late summer. Strong, zonal midlatitude westerlies exist south of 30°N. Twelve hours later (Fig. 38b), the STA center over the U.S. is dissipating, and the ECPac STA is zonally oriented. TD 01E is in a

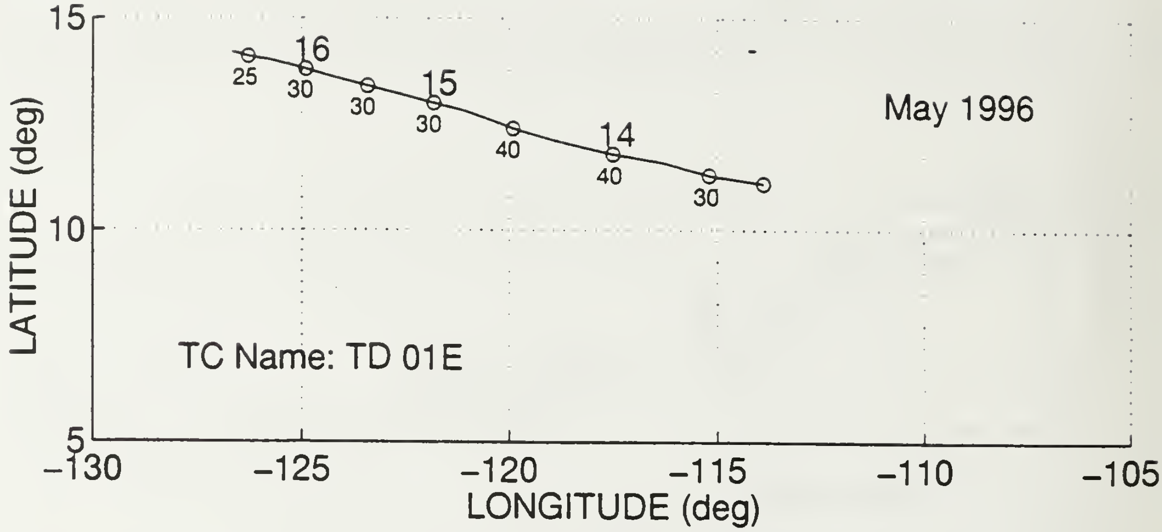


Figure 37. Best track, as in Fig. 34, except for TD 01E in May 1996.

transitional state from S/RE to S/RP. During the next 24 h (Fig. 38c,d), the orientation of the STA becomes tilted northwest-southeast in response to the SRM transitional mechanism. Thus, TD 01E moves northwestward in the S/RP pattern/region. Usually when the STA is modulated, a particular midlatitude trough or ridge is involved, and SRMT or SRMR is noted. In this case, the entire environment is relatively zonal, so just a general SRM is recorded.

It is noted that this configuration of the STA is unorthodox during the off-season, and the NOGAPS analyses have differences from the S/RP environment of the S pattern schematic (Fig. 16). Nevertheless, the orientation of the STA is still the determining factor for TC motion for such cases.

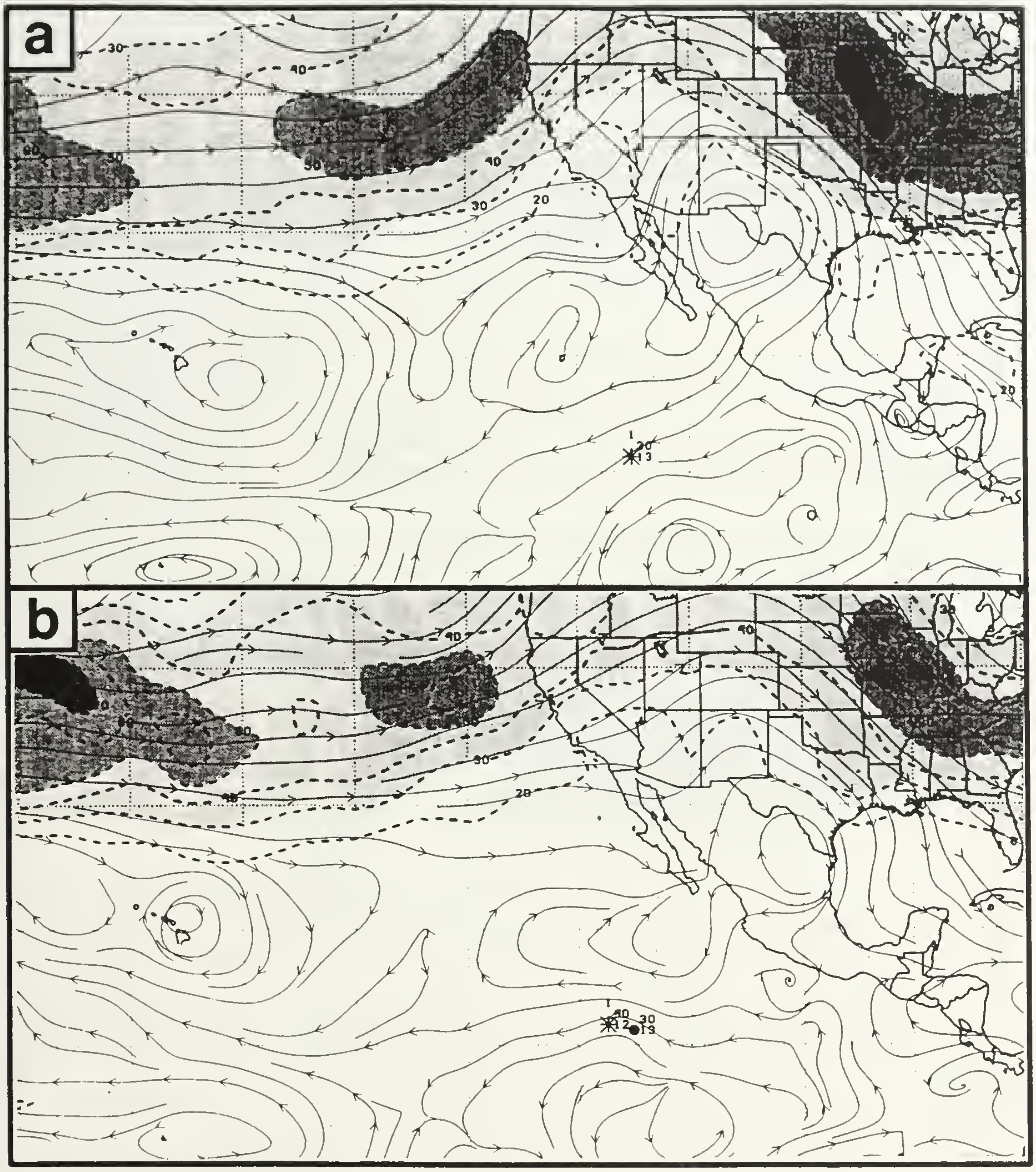


Figure 38. NOGAPS 500-mb analyses as in Fig. 17, except at (a) 12 UTC 13 May and (b) 00 UTC 14 May 1996.

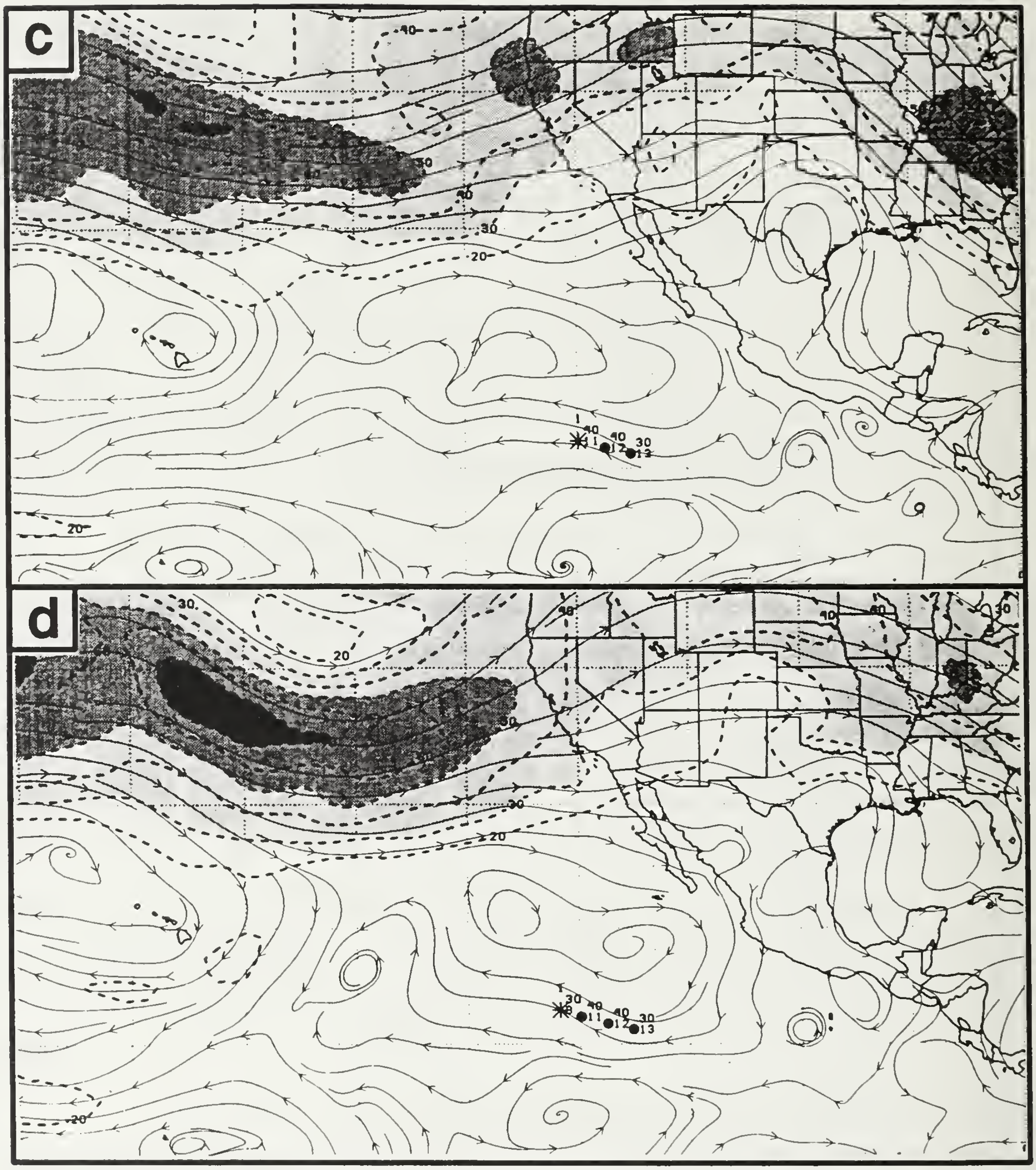


Figure 38. (continued) Like (a), except at (c) 12 UTC 14 May, and (d) 00 UTC 15 May 1996.

d. S/RP to S/WR to S/RP (TS Elida 1996)

TS Elida was introduced earlier this chapter (Fig. 17) as an example of a TC in the S/RP pattern/region . This case study describes how Elida subsequently performed a transition from S/RP to S/WR. As mentioned before, TCs that are advected into a break in the STA from S/RP usually do so in response to a passing midlatitude trough via the SRMT process, and this is the case here.

At 00 UTC 1 September 1996 (one day after the time of Fig. 17), the TC is still moving northwest (Fig. 39) in the S/RP pattern/region (Fig. 40a). The eastern branch of the STA is tilted northwest to southeast from southern California to the Bay of Campeche, and the isotach maximum is to the east of the TC. Notice a cutoff low near 18°N, 129°W is having little effect.

One day later (Fig. 40b), the synoptic situation is quite different. First, the midlatitude trough has deepened over California, and the STA has been weakened to the north of Elida. Second, the cutoff low has drifted toward the west and is concurrently building a stong peripheral anticyclone to the west of Elida. The weakening of the STA by the trough via the SRMT process in conjunction with the building of the anticyclone to the west has placed Elida in a WR region in the break region of a relatively zonal STA. In response, the translation speed of Elida slows to 5 kt while temporarily moving west-northwest (Fig. 39) in weak steering flow.

On 3 September (Fig. 40c), Elida is still in the WR region, and is moving in the expected poleward direction, but has accelerated from 3 kt 12 h earlier to currently 6 kt.

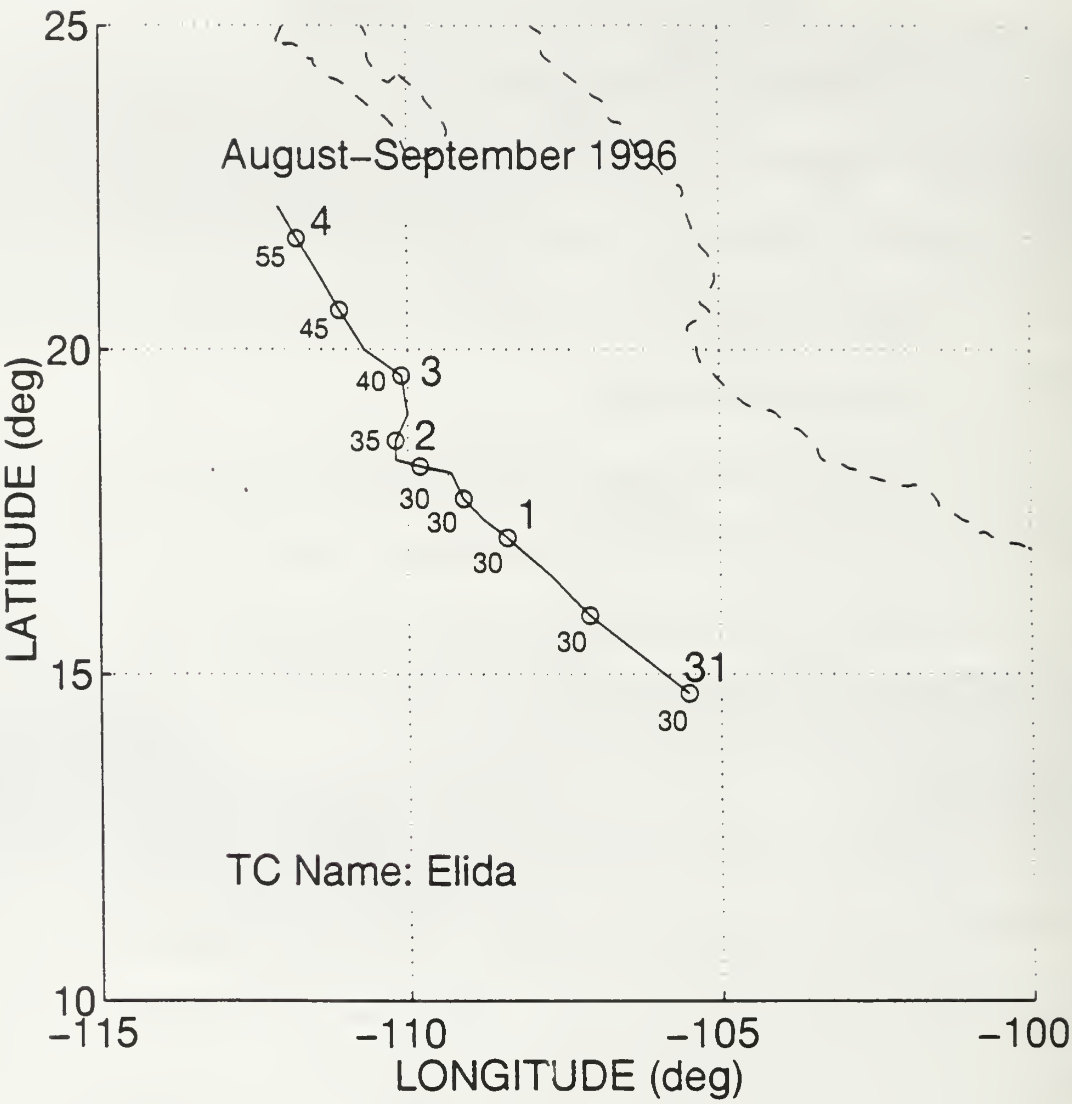


Figure 39. Best track, as in Fig. 34, except for TS Elida in August-September 1996.

The peripheral anticyclone of the cutoff low is tending to create a ridge to the west side of Elida. Because the midlatitude trough was a transient feature, the STA is starting to build again to the north.

After another day (Fig. 40d), the STA to the north is now stronger than the peripheral anticyclone, which is dissipating along with the cutoff low. Thus, Elida is back

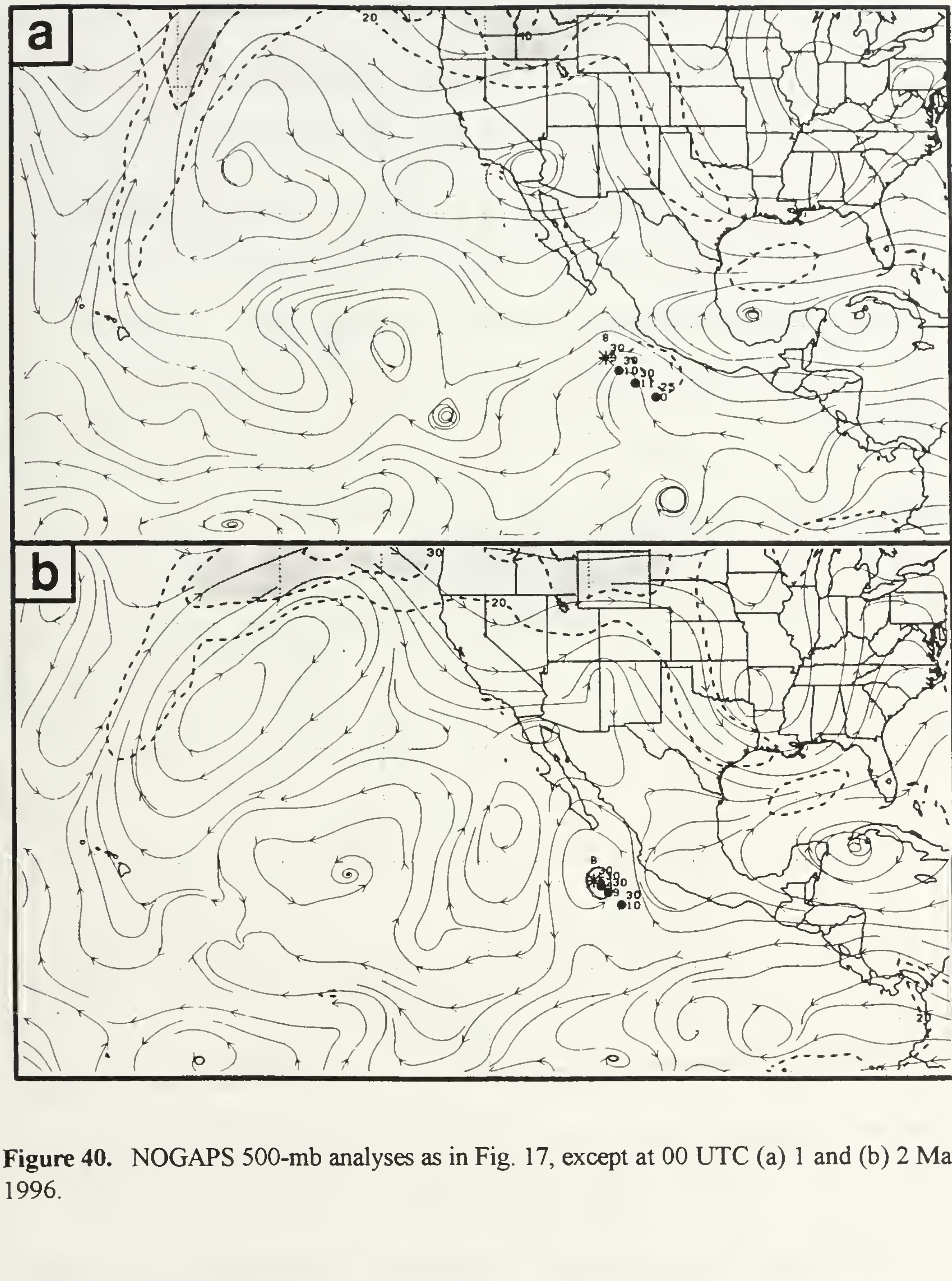


Figure 40. NOGAPS 500-mb analyses as in Fig. 17, except at 00 UTC (a) 1 and (b) 2 May 1996.

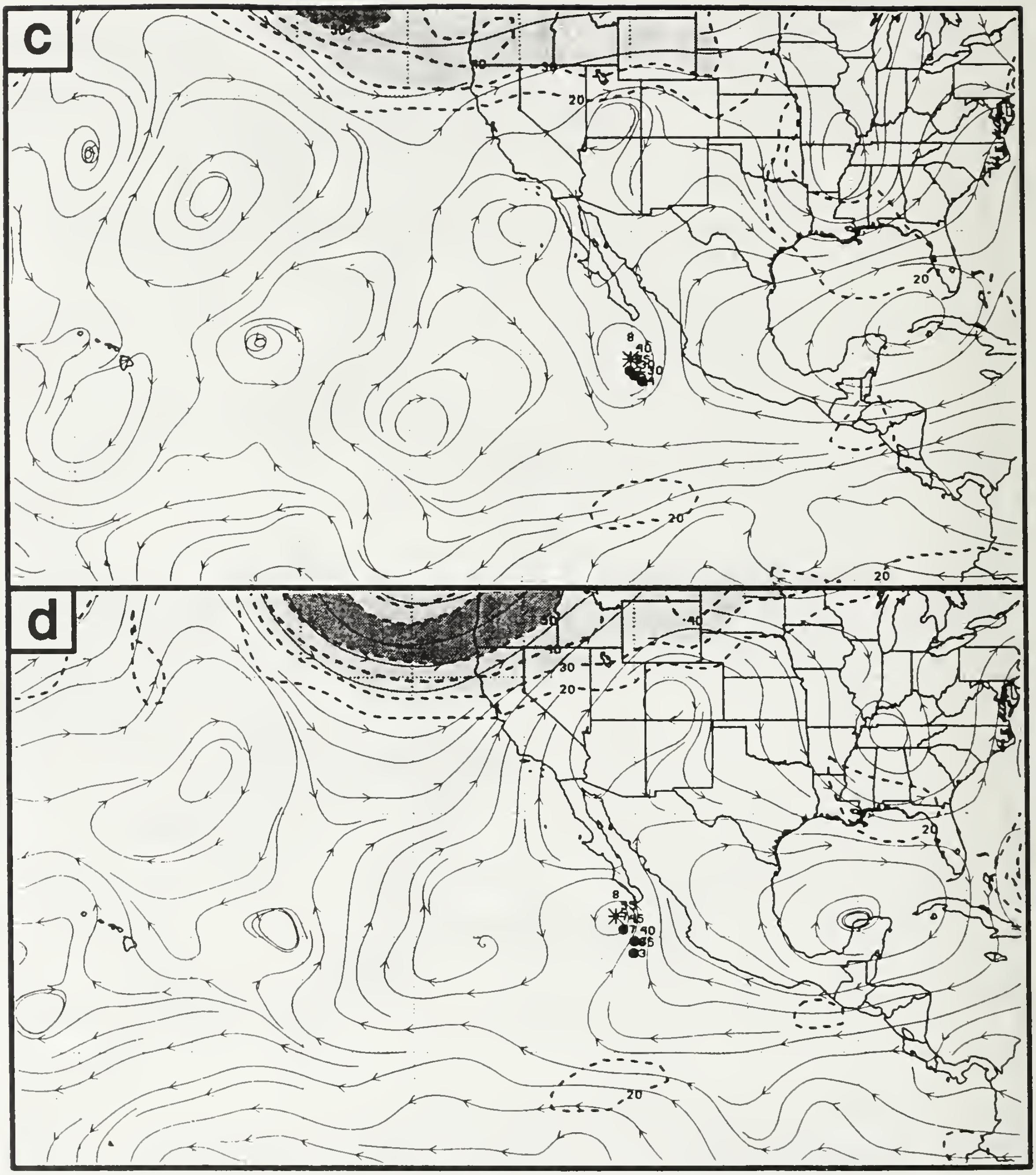


Figure 40. (continued) Like (a), except at 00 UTC (c) 3 and (d) 4 May 1996.

in the southeasterlies of the S/RP pattern/region. The dependence of the TC environment structure in the S/RP pattern/region on passage of a midlatitude circulation to help move poleward through the STA axis means that the TC is dependent upon transient features. This return to the original environment structure is not uncommon as the midlatitude trough that helps break the STA translates eastward, and the STA then tends to build back in place.

e. S/RE to S/WR to S/MW (Hurricanes Kenneth and Lidia 1993)

The Elida case study demonstrated that the weakening of the STA by a trough via the SRMT process may not be enough to allow a TC to move poleward of the STA axis from the S/RP into the S/MW pattern/region. The track of Hurricane Lidia (Fig. 41) appears

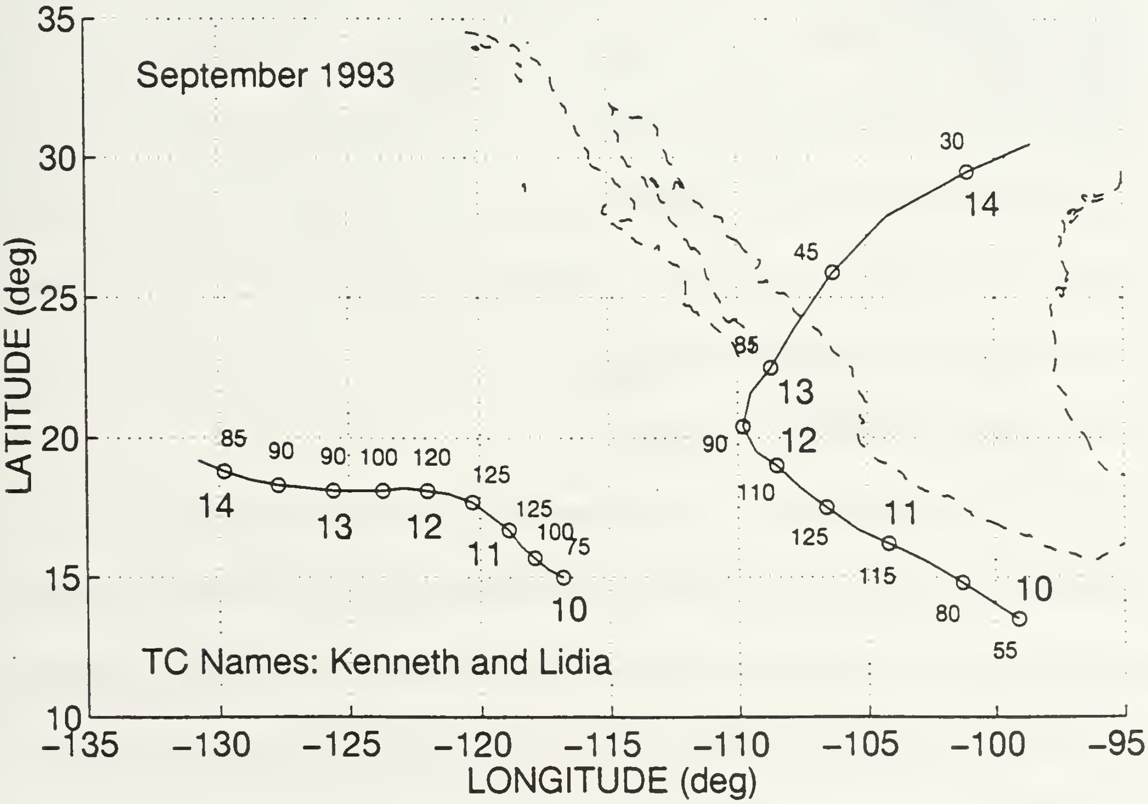


Figure 41. Best track, as in Fig. 34, except for Hurricanes Kenneth (west) and Lidia (east) in September 1993.

like a "typical" recurvature track, but the turn poleward was helped by the extra effect of another hurricane.

At 00 UTC 10 September 1993 (Fig. 42a), Hurricane Kenneth (TC #12) is in a transitional state. Although embedded in the northeasterlies of the S/RE pattern/region, a peripheral anticyclone has been building to the southeast of Kenneth via the RMT process. A recent turn from west-southwest to northwest and the shift of the 30-kt isotach maximum from north to east of the TC are evidence of a transition from the S/RE to P/PO pattern/region. Meanwhile, Lidia (TC #13) is well east of the STA apex in the S/RP pattern/region and is moving toward the northwest.

By 00 UTC 11 September (Fig. 42b), the TCs are interacting indirectly as Lidia is advancing toward the peripheral anticyclone of Kenneth. Although Kenneth is still currently moving northwestward in the S/RE to P/PO transitional state, the TC is undergoing the ITIW transitional mechanism in which the peripheral anticyclone is being dissipated by cyclonic vorticity advection associated with the eastern TC Lidia. Thus, the transition of Kenneth into the P/PO pattern/region is soon to be aborted. Lidia continues to move northwestward in the S/RP pattern/region.

A day later (Fig. 42c), the separation distance between the two TCs has decreased to 16° latitude, and they are now interacting semi-directly as the intermediate anticyclone has almost been eliminated. Although a 30-kt isotach maximum is to the east of Kenneth on the NOGAPS analysis, Kenneth is moving almost due west rather than to the north. The implication is that NOGAPS is maintaining for too long the strength of the

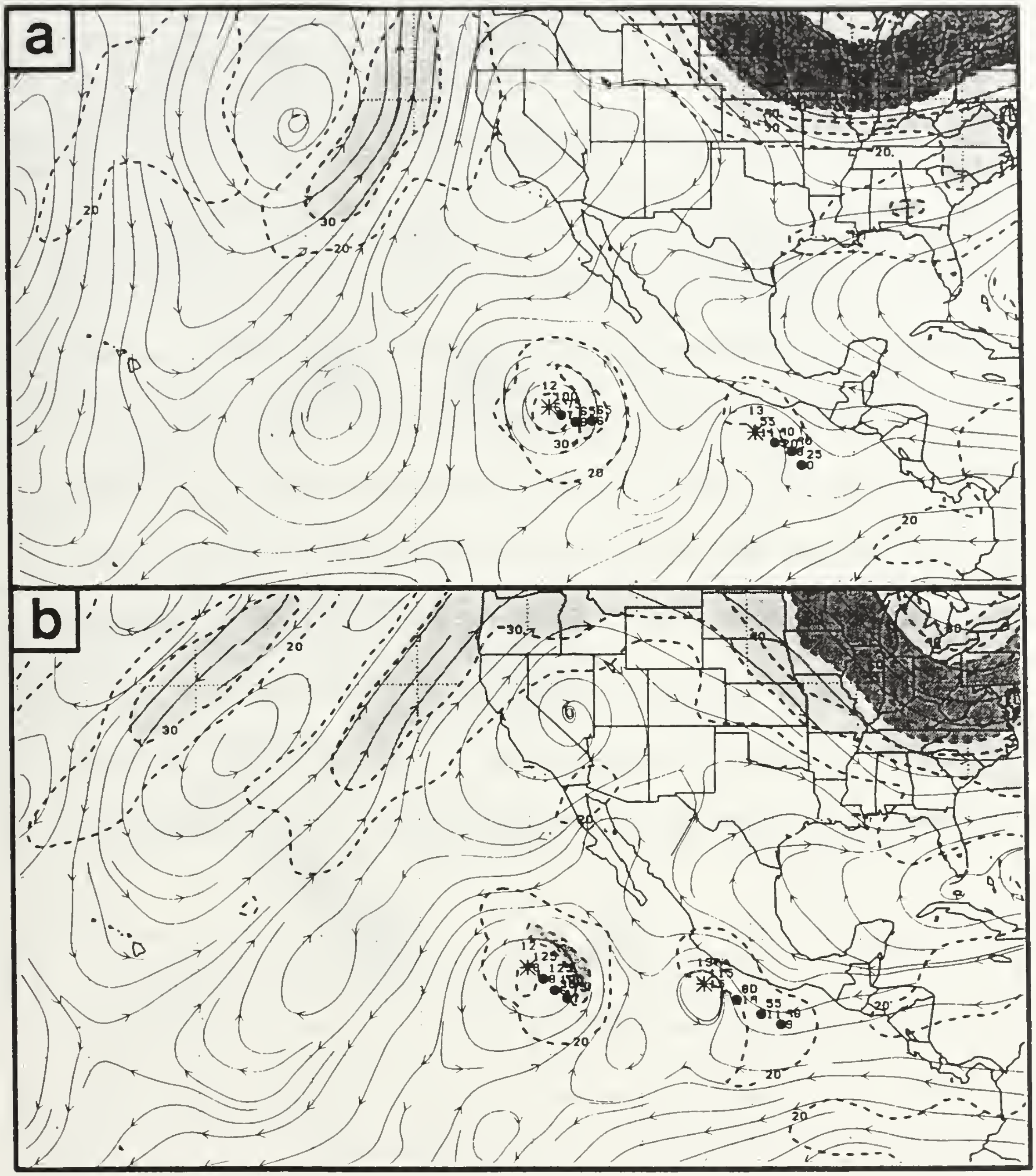


Figure 42. NOGAPS 500-mb analyses as in Fig. 17, except at 00 UTC (a) 10 and 11 September 1993.

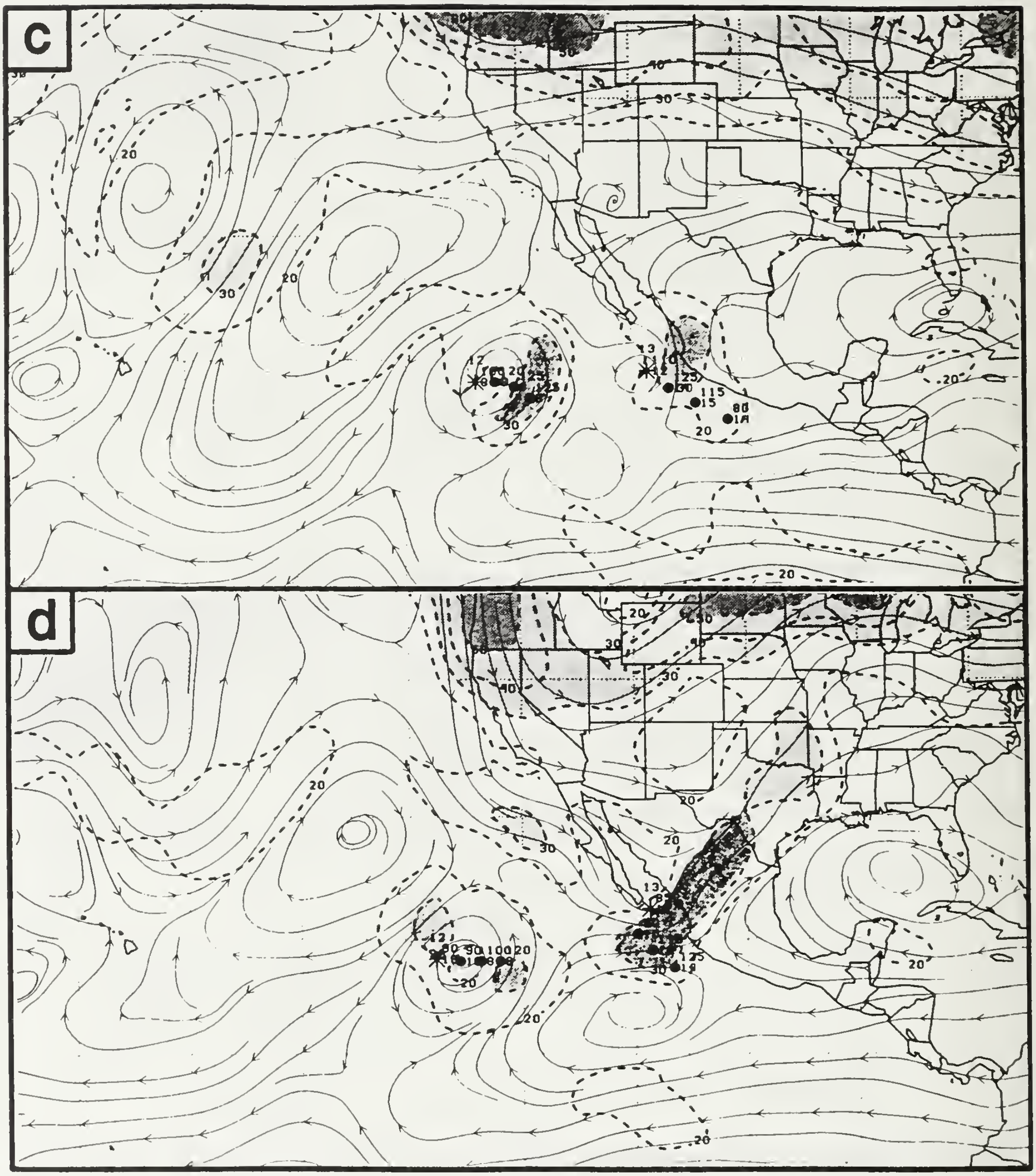


Figure 42. (continued) Like (a), except at 00 UTC (c) 10 and (d) 11 September 1993.

peripheral anticyclone that Lidia helped dissipate. Even though Kenneth is still in the northeasterlies of the S/RE pattern/region, the presence of Lidia to the east has also placed Kenneth in a transitional state from S/RE to M/EF via the STIW transitional mechanism. Considering that Kenneth is not travelling south of west even though Lidia is nearby and the environmental flow has a strong equatorward component, a complete transition to M/EF can not be recorded. However, the presence of Lidia to the east potentially has an effect and the environment of Kenneth is considered transitional toward M/EF. Meanwhile, Lidia is undergoing the STIE transitional mechanism owing to the low pressure associated with Kenneth and the high pressure in the STA cell farther east. Notice also that Lidia is not slowing down as it approaches the STA axis. Thus, Lidia has completed a transition from the S/RP to M/PF pattern/region. Whereas the location of the eastern STA cell so close to Lidia helps the TC make the complete transition to the M pattern, the larger distance between Kenneth and the tilted STA to the northwest is consistent with a non-completed transition.

The semi-direct interaction with Kenneth helped move Lidia poleward into a WR region, and by the next day (Fig. 42d), a substantial midlatitude trough has broken the STA. This is another example of the SRMT process, and Lidia is near the base of the trough and is moving northeast in the S/MW pattern/region. The isotach maximum to the east of Lidia is now connected with the isotachs of the downstream midlatitude trough. Although the environment around Lidia appears similar to the P pattern with a peripheral anticyclone and isotach maximum to the southeast, Lidia is considered to be in S pattern because Lidia

was already north of the STA axis when the peripheral anticyclone finally became strong. The initial southeasterlies in the S/RP pattern/region, followed by the effects of the STIE and SRMT processes, were the causes for the poleward motion of Lidia, not the recently developed peripheral anticyclone. Notice that as Lidia is moving away from Kenneth, the M pattern breaks down. Therefore, Kenneth is simply in the S/RE pattern/region even though evidence of a building peripheral anticyclone via the RMT process is present in the NOGAPS analysis.

f. S/RE to S/WR to S/MW to S/WR to S/RE (Hurricane Trudy 1990)

The previous case studies have demonstrated the importance of midlatitude troughs breaking the STA via the SRMT process in order for TCs to move from the S/RP to the S/WR pattern/region. However, almost three times as many TCs move into the WR region from the RE region (30 transitions) than from the RP region (11 transitions) (Fig. 33). Hurricane Trudy of 1990 made this fairly common transition, while also being affected by the SRMT process, and subsequently the SRMR process.

At the beginning of 19 October 1990, Hurricane Trudy is travelling west in the S/RE synoptic pattern/region (Fig. 43). The NOGAPS 500-mb analysis of 12 h later (Fig. 44a) depicts the slightly tilted STA that is creating the RE region. Notice the expected 20-kt isotach maximum to the north of a westward-moving TC. However, a passing midlatitude trough is beginning to weaken the STA to the northwest, and Trudy is turning to the northwest in response to this SRMT process.

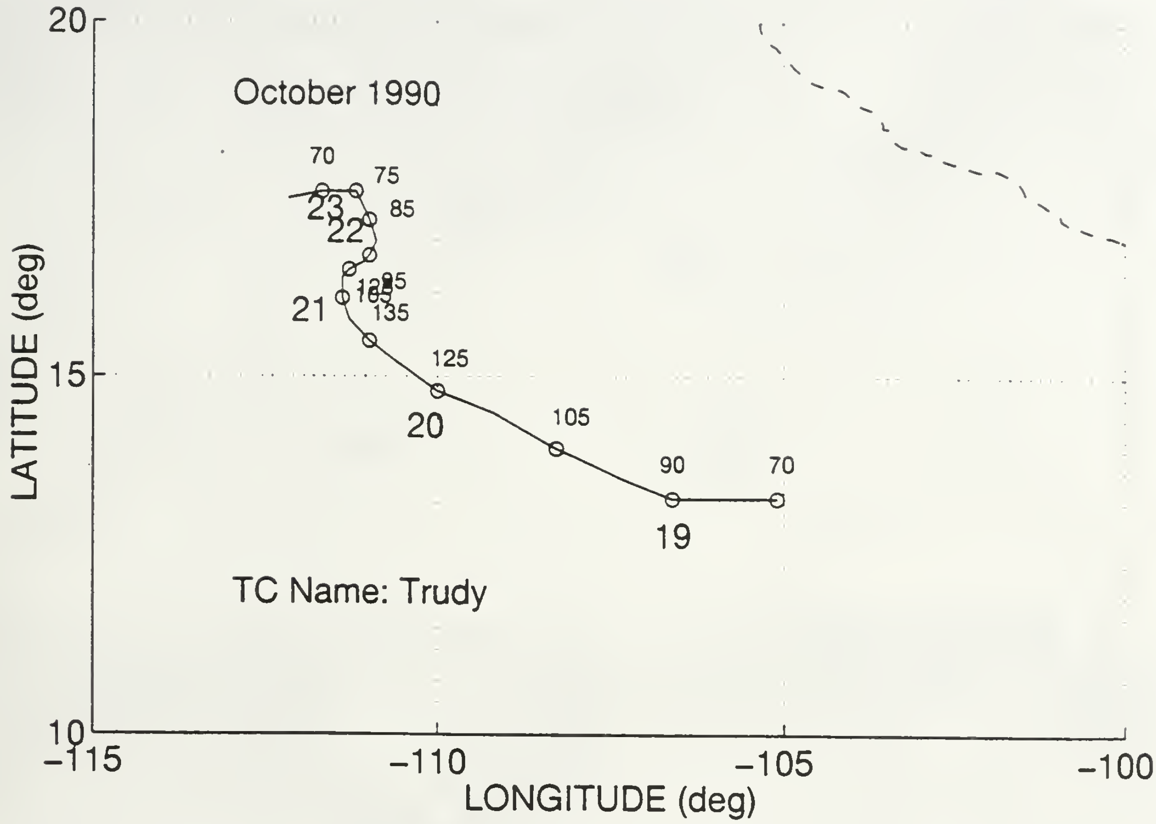


Figure 43. Best track, as in Fig. 34, except for Hurricane Trudy in October 1990.

Twenty-four hours later (Fig. 44b), Trudy is in a col within the STA and has slowed to a 5 kt translation speed with the isotach maximum to the east. Thus, Trudy has completed the common S/RE to S/WR transition via the SRMT process. At 12 UTC 21 October (Fig. 44c), Trudy is moving toward the northeast after having just completed another transition from the S/WR to S/MW pattern/region. Although the isotach maximum is still to the east on the NOGAPS analysis, the east of north motion of the TC indicates a transition in the MW region. Meanwhile, the midlatitude trough that created the break continues to move east, and the trailing ridge is moving to the east.

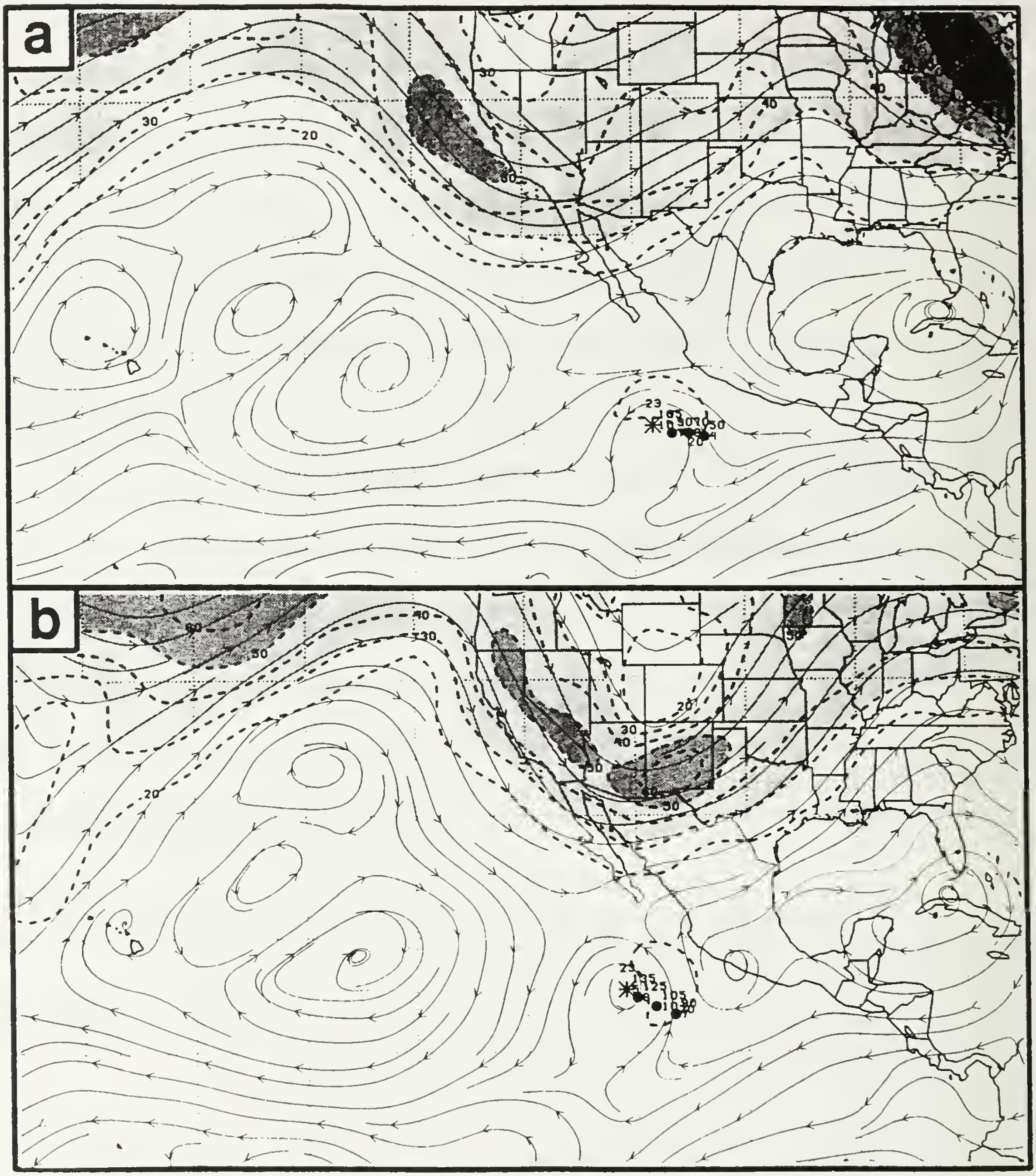


Figure 44. NOGAPS 500-mb analyses as in Fig. 17, except at 12 UTC (a) 19 and (b) 20 October 1990.

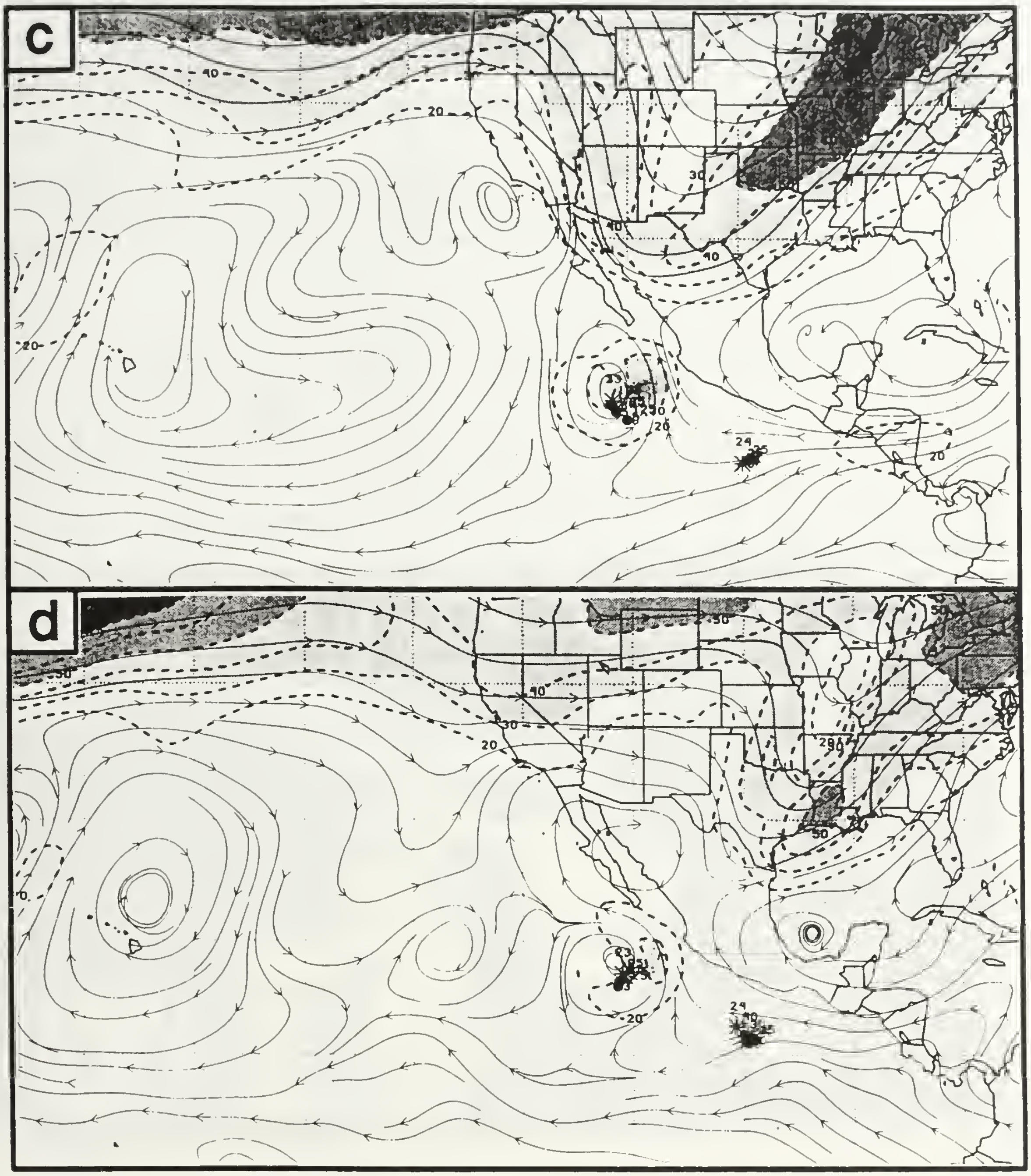


Figure 44. (continued) Like (a), except at 12 UTC (c) 21 and (d) 22 October 1990.

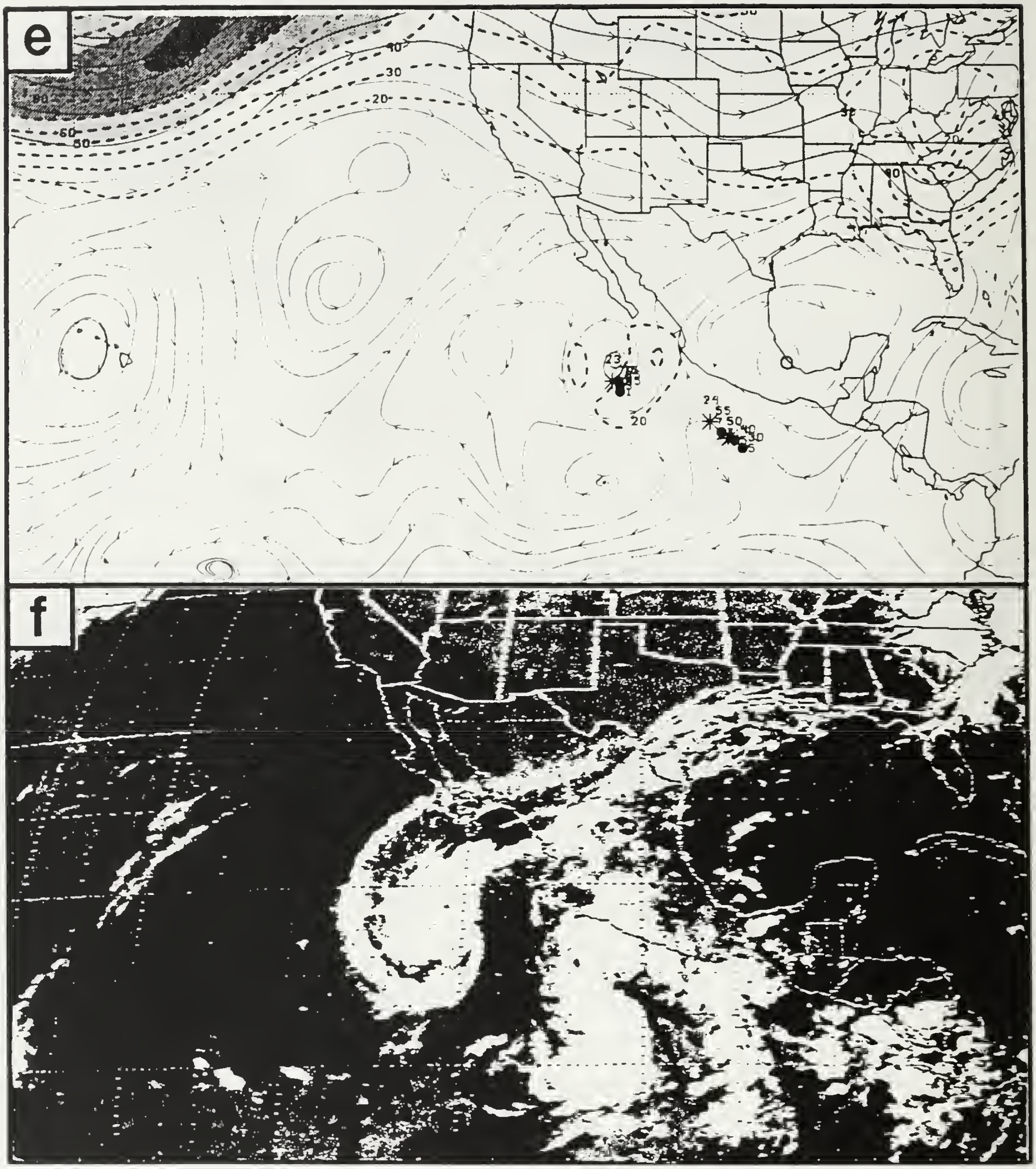


Figure 44. (continued) (e) 12 UTC 23 October 1990 and (f) GOES infrared imagery at 0901 UTC 23 October 1990.

At 12 UTC 22 October (Fig. 44d), the transient midlatitude trough/ridge feature is farther east, so that the ridge is now to the north in the path of the TC. Owing to this SRMR process, Trudy is now surrounded by anticyclones on three sides, and has made a transition from the S/MW pattern/region back to the S/WR pattern/region. Such a transition was recorded six times during the 7-y sample (Fig. 33).

At 12 UTC 23 October (Fig. 44e), Trudy is moving west and has made a change from S/WR back to the original S/RE pattern/region, which is the third most common transition (Fig. 33). Another transition to M/EF is imminent with the approach of TS Vance from the southeast. In the GOES infrared imagery three hours prior to the last NOGAPS analysis (Fig. 44f), Trudy appears relatively intact and still vertically structured. The anticyclones surrounding the TC have decreased the vertical wind shear and allowed it to remain intense. Many TCs in the ECPac make a "return" transition from the WR region back to the RE region, but for TCs to turn equatorward via the SRMR process as experienced by Trudy is relatively rare.

g. S/WR to S/RE via VWS (TS Miriam 1994)

While the SRMR transitional mechanism may be a rather uncommon reason for an ECPac TC such as Trudy to return from the S/WR to S/RE pattern/region, the TC-environment transition process known as vertical wind shear (VWS) is by far the most common. In the WPac sample, VWS was used only to describe the rare sudden track change when a TC is sheared apart by the interaction with an upper-level westerly jet during the off-season winter monsoon. In ECPac, the westerlies in the base of digging midlatitude troughs

advect the mid- and upper-levels of the TC to the northeast, and leave the low-level circulation behind. This process is considered to be a transitional mechanism not because it necessarily changes the environmental flow at the 500-mb level, rather because it leaves only a less intense TC that is being steered at a lower level.. That is, VWS essentially changes the environment that is controlling the TC motion from 500 mb down to a lower level, which may be quite different from the environment at the mid-troposphere. TS Miriam in 1994 is one of many ECPac TCs to experience the VWS transitional mechanism.

The best track of TS Miriam (Fig. 45) has one major turn that may be difficult to forecast. At 00 UTC 18 September 1994 (Fig. 46a), Miriam is in a transitional state moving from the S/RE pattern/region of the typical bowed STA to the S/WR pattern/region. Both the BEP of the TC as well as the breaking of the STA by a midlatitude trough are facilitating this transition. Twelve hours later (not shown), Miriam completes the transition. By 00 UTC 19 September (Fig. 46b), the environment of the TC has changed.

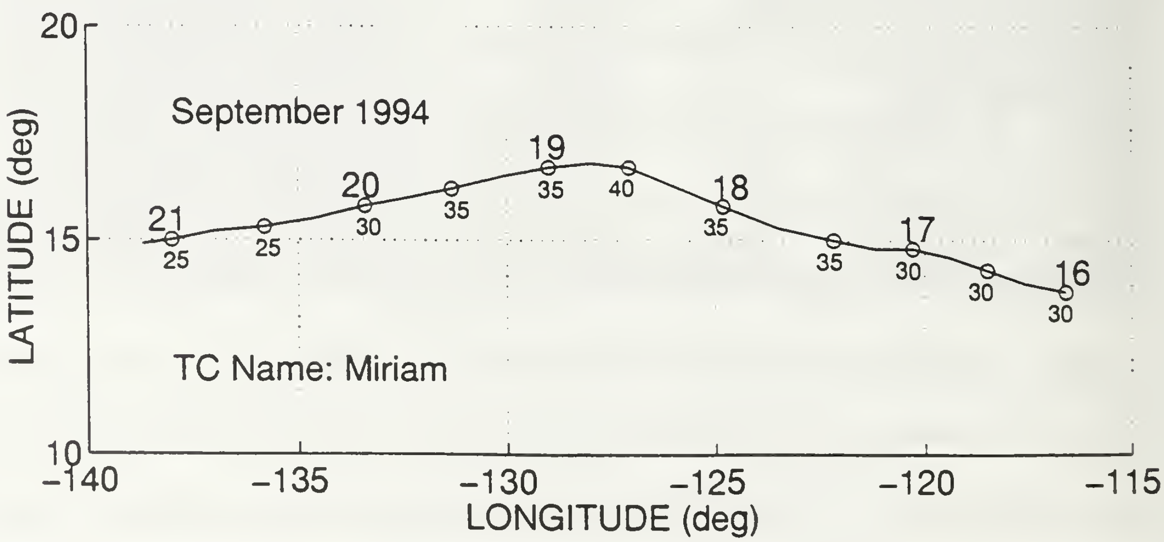


Figure 45. Best track, as in Fig. 34, except for TS Miriam in September 1994.

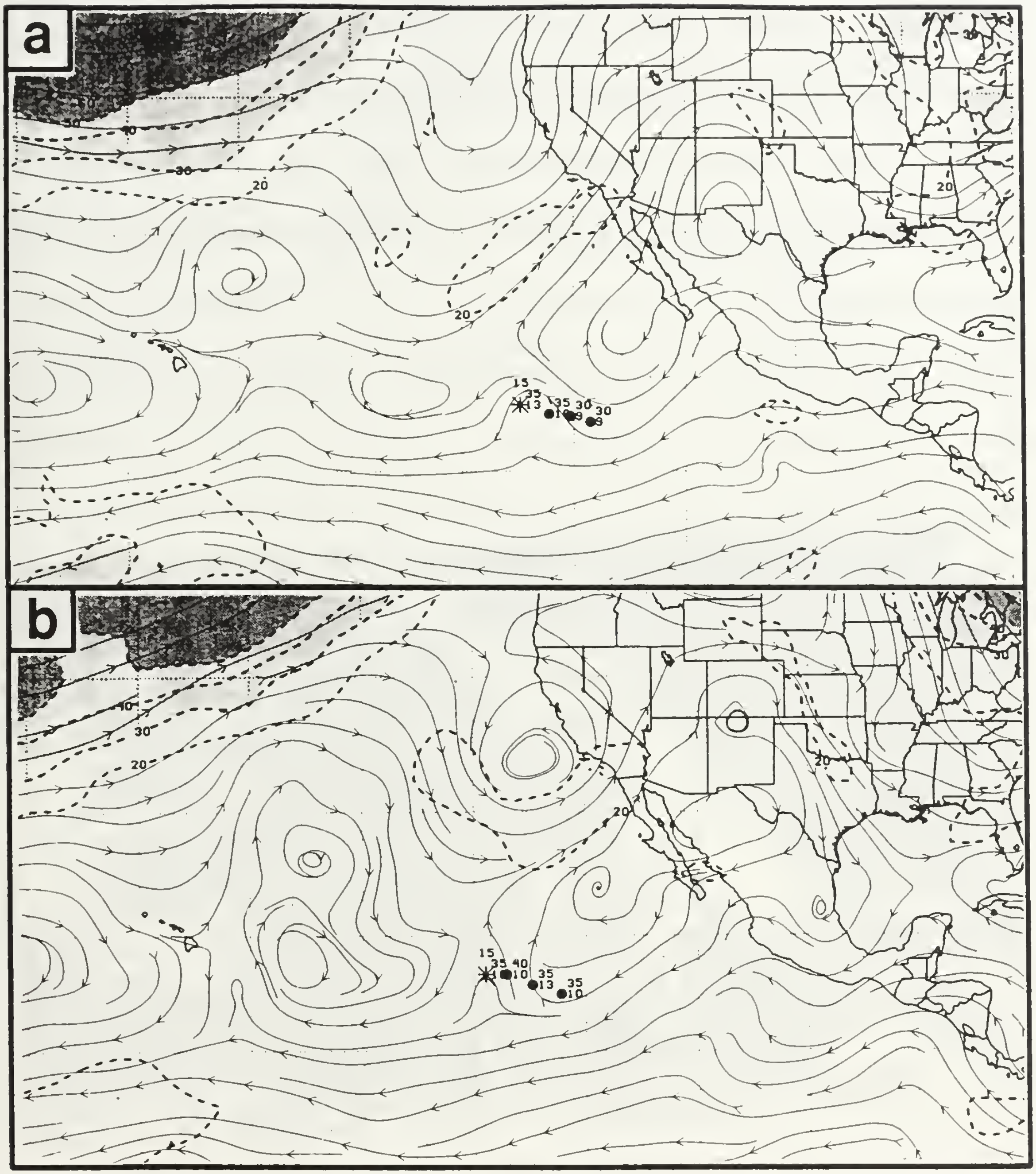


Figure 46. NOGAPS 500-mb analyses as in Fig. 17, except at 00 UTC (a) 18 and (b) 19 September 1994.

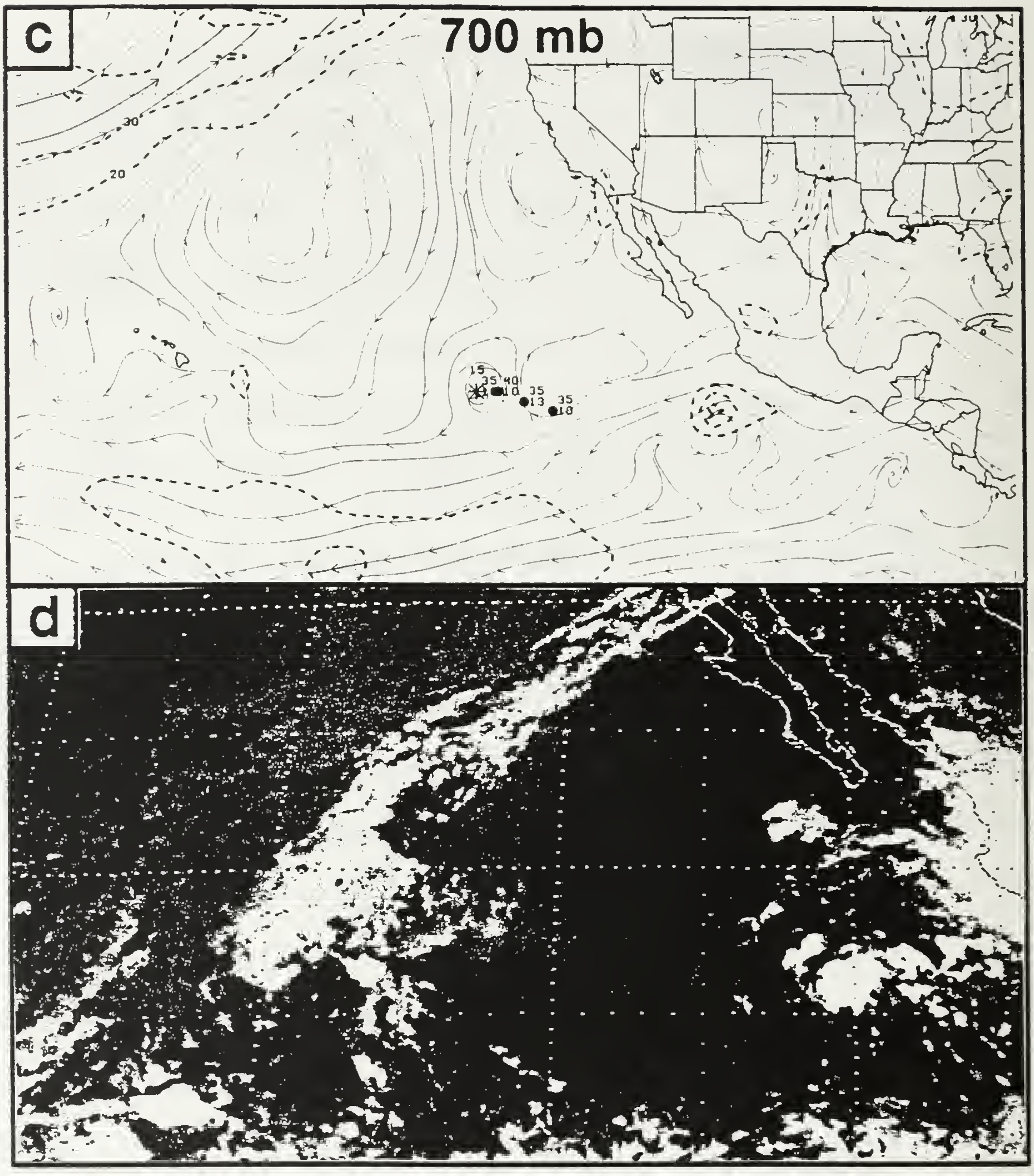


Figure 46. (continued) (c) Like (b), except 700-mb analysis. (d) GOES infrared imagery at 0501 UTC 19 September 1994.

Although Miriam appears to still be in the WR region between two similar-sized anticyclones on the NOGAPS 500-mb analysis, the westerly winds at the base of the trough have sheared the TC apart. The more appropriate steering level for the less intense TC center has been lowered to about 700 mb. The NOGAPS 700-mb analysis is much different from the 500-mb analysis (Fig. 46c). A large anticyclone is to the northwest while only a small anticyclone is to the east. Miriam is now back in the S/RE pattern/region, with an environment of the northeasterlies on the southeast flank of a circular anticyclone over the ocean rather than the typical tilted STA at 500 mb. The reduced central convection with a plume of upper-level moisture streaming to the northeast depicted in GOES infrared imagery at 05 UTC (Fig. 46d) is striking evidence of the VWS process.

A large number of ECPac TCs experienced VWS during the 7-y sample (Fig. 47). More importantly, many of the tracks of these TCs exhibit the sudden northwest to

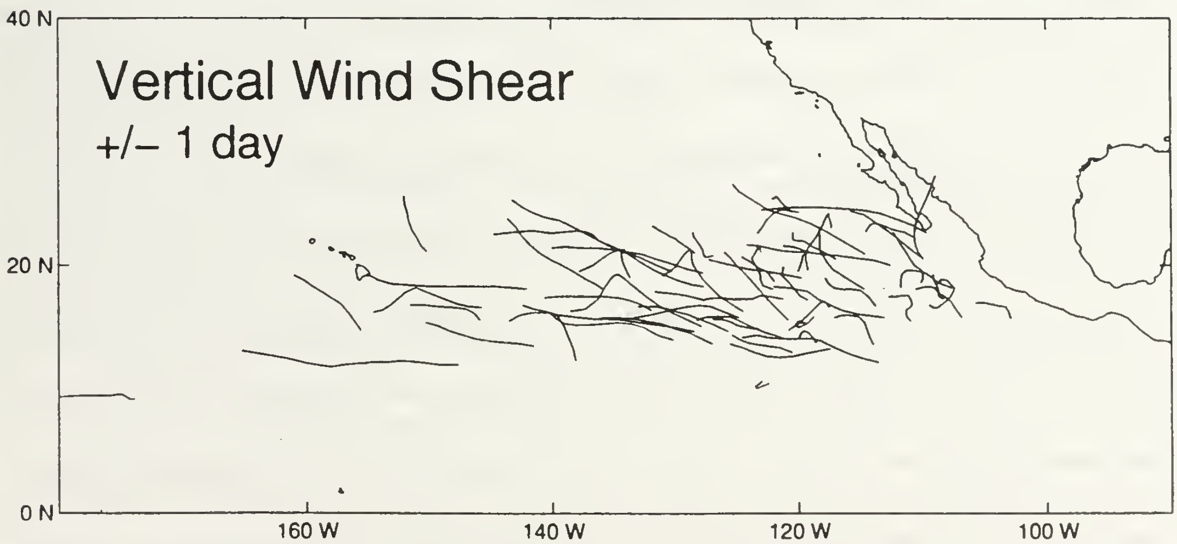


Figure 47. Tracks as in Fig. 1, except only when the TCs were undergoing the VWS transitional mechanism with up to a day before and after the process plotted. Circles at the ends of the tracks have been omitted in order to make the tracks more visible.

southwest turn as is the case of Miriam. This insight into TC motion following the VWS process is valuable information for the forecaster who might make large errors during this difficult scenario.

h. ITIE (Hurricanes Frank and Georgette 1992)

The ITIE process in which an eastern TC turns equatorward owing to the peripheral anticyclone of another TC to the west may not result in an environment structure transition. However, the turn of the TC may be substantial and perhaps unexpected. This transitional mechanism affects about two TCs a year in the ECPac.

The track of Hurricane Frank is straight and toward the northwest, while that of Hurricane Georgette has two turns within two days (Fig. 48). The STA to the north of the TCs at 12 UTC 19 July 1992 (Fig. 49a) is oriented zonally, which is unusual in the ECPac. Thus, the distinction between RP and RE is less meaningful. Nevertheless, Frank is considered to be in the S/RE pattern/region because it is west of the main STA center, while Georgette is in S/RP pattern/region because it is east of the center. Whereas both are of hurricane intensity, Frank is considerably larger than Georgette in the satellite imagery (Fig. 49b). Although they are separated by only 15° latitude, their positions well south of the STA axis is not favorable to establish an increased pressure gradient that is required for the M pattern or the STI process. Both TCs are moving to the northwest, and the western Hurricane Frank is moving more quickly at 15 kt compared to the 9 kt translation speed of Georgette. Even though a connected peripheral anticyclone is developing via the RMT

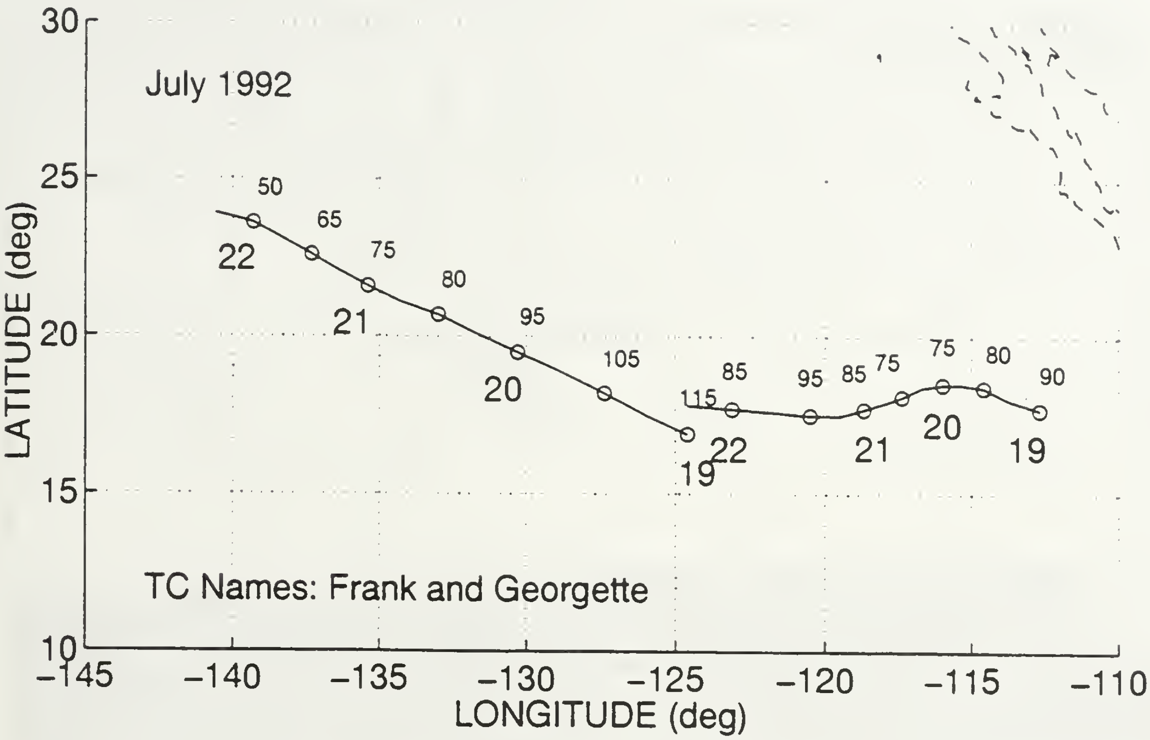


Figure 48. Best track, as in Fig. 34, except for Hurricanes Frank (west) and Georgette (east) in July 1992.

process to the southeast of the two TCs, the STA to the north is still the dominant circulation advecting the TCs.

By 12 UTC 20 July (Fig. 49c), Frank has moved farther west and increased the separation between the TCs. Because of this separation, the Rossby wave dispersion of the two TCs is not acting constructively. The peripheral anticyclone in the NOGAPS analysis is now to the southeast of only the large Hurricane Frank. Georgette is in the equatorward flow on the east side of this peripheral anticyclone and travelling slowly to the southwest at 7 kt while Frank continues to move quickly to the northwest (Fig. 48). Notice in Fig. 49c that separate 20-kt isotach maxima are associated with each TC, with one to the

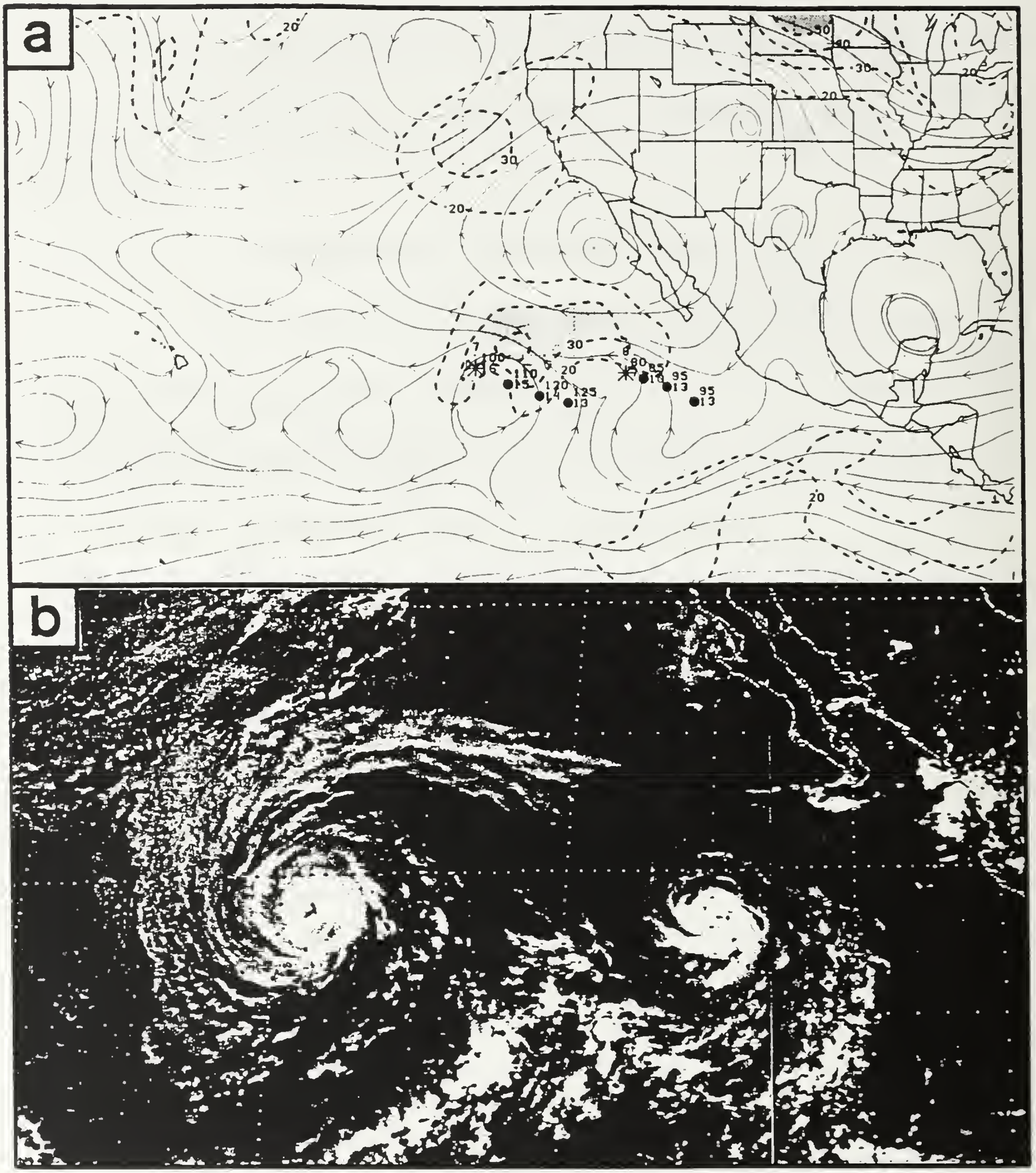


Figure 49. (a) NOGAPS 500-mb analysis as in Fig. 17, except at 12 UTC 19 July 1992. (b) GOES visible imagery at 1731 UTC 19 July 1992.

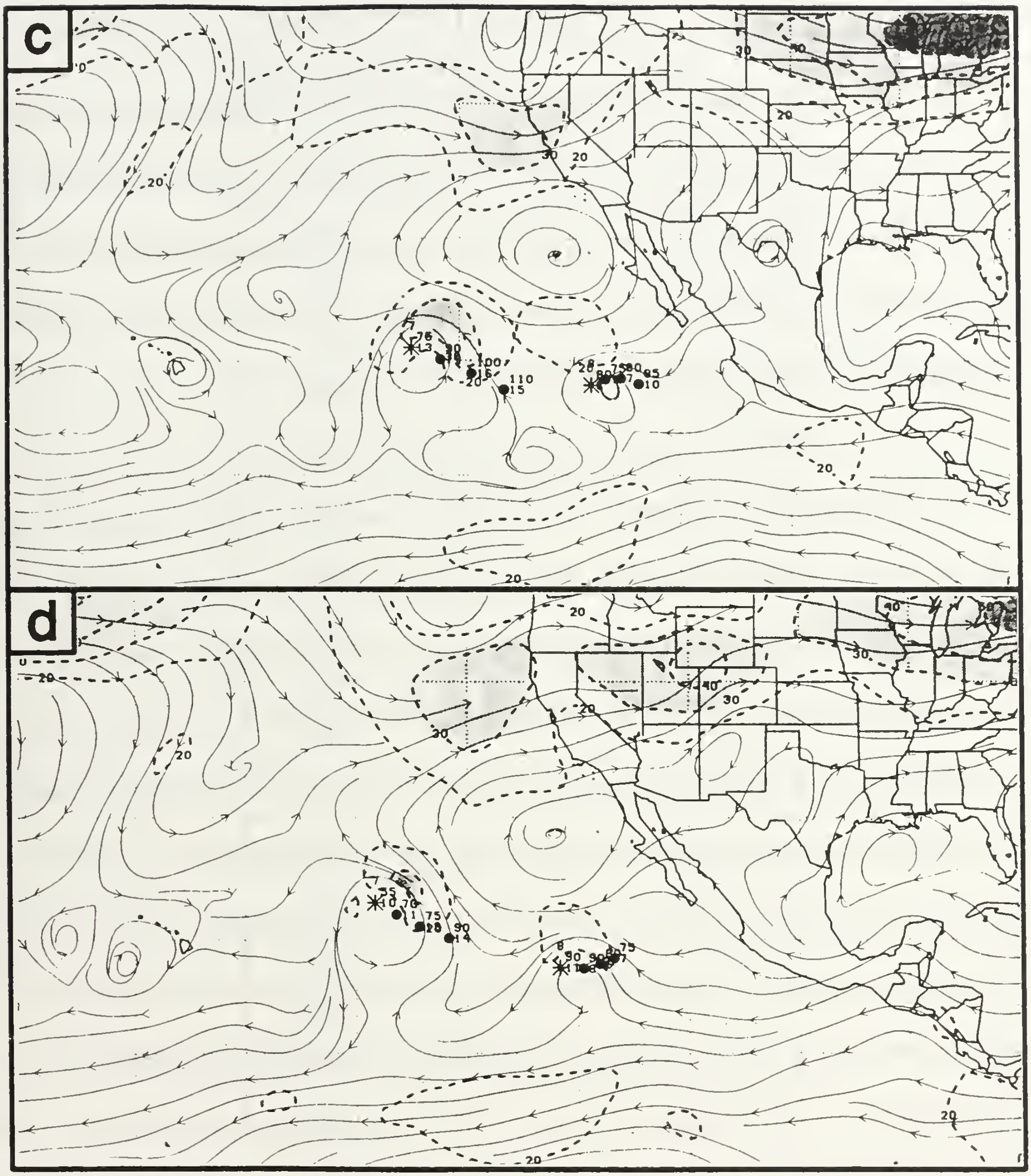


Figure 49. (continued) Like (a), except at 12 UTC (c) 20 and (d) 21 July 1992.

northeast of Frank and the other to the northwest of Georgette, which is consistent with their respective motions.

A day later (Fig. 49d), Frank is moving into the S/WR pattern/region and experiencing VWS by midlatitude westerlies. As Frank dissipates, so too does the peripheral anticyclone. Although they are still analyzed, the peripheral anticyclone and the equatorward flow on the east side are weaker, and Georgette has turned back to a westward heading, and thus has completed a second turn in as many days.

3. Summary

The previous case studies have examined the most common transitions and transitional mechanisms that occur in the ECPac. A summary is presented in Table 2 of the number of TCs affected by all of the transitional mechanisms in Fig. 14. Notice that TCs may experience more than one of these during a lifetime, and sometimes a single transition is caused by two of these mechanisms acting simultaneously. Notice that the two types of mechanisms most associated with the midlatitudes, namely the three variations of SRM and VWS, affect the most TCs with counts of 86 and 51, respectively. Here, the SRM mechanism is separately listed in three parts, so that SRMT (SRMR) implies that a passing midlatitude trough (ridge) is critical, while SRM indicates other cases in which both a trough and ridge play a part in changing the STA. An influence of a passing trough is more common than that of ridges because troughs initiate breaks in the STA that affect TCs to the south such that poleward motion into the westerlies is favored. In many ECPac cases, the TC is quickly sheared via VWS so that the steering flow is shifted to lower levels. These

TRANSITIONAL MECHANISMS	NO. TCs
Environment Effects	
ADV	**47**
MLF	**6**
MLD	**1**
SRM	**30**
SRMT	**41**
SRMR	**15**
TC-Environment Transformations	
BEP	
RMT	**34**
MTF	**2**
DTI1	**3**
DTI2	**4**
DTI3	**2**
STIE	**6**
STIW	**5**
ITIE	**8**
ITIW	**2**
VWS	**51**
ORO	**8**

Table 2. Number of TCs that undergo the corresponding transitional mechanisms. If a mechanism affects a TC at any point, the TC is counted once, regardless of duration of the mechanism or whether or not the mechanism occurs again at a future time. Because BEP is occurring constantly with all TCs and the effect is hard to determine for transitions, it is not counted. For MTF, DTI2, and DTI3, which act simultaneously upon two TCs, both TCs are counted so that a 2 listed above refers to one occurrence.

TCs are then not affected by the trailing mid-latitude ridge, which would be classified as SRMR. Notice that simple ADV from one region to another within the S pattern is also common, which is expected considering the large number of TCs in that pattern.

Several of the transitional mechanisms in Table 2 were not presented in the case studies. The environment effects of Mid-level Low Formation/Dissipation (MLF/MLD) are equivalent to the mechanisms presented in the monsoon gyre description of the WPac (Carr and Elsberry 1994). Roughly one TC a year is found in the L/PO pattern/region of a forming cutoff low. When ECPac TCs are on the periphery of a cutoff low, they are being advected poleward and tend to dissipate quickly over cool waters. Hence, only one TC in the 7-y sample lasted longer than the low and experienced an environment structure change because the low dissipated first. Also, no ECPac TCs were observed to merge with the low circulation, as in the WPac Monsoon gyre-TC Interaction (MTI) transformation because the thermodynamic structure of the cold-core low is an unfavorable environment for sustaining a TC. Hence, the difficult-to-forecast TC-Low merger scenario is rare and need not be of concern.

The BEP TC-environment transformations are not counted in Table 2 because BEP is always occurring, and it is difficult to determine if propagation plays a role in a particular transition. The count for the RMT process indicates that roughly one-fourth of all TCs have conditions that may lead to an attempt at the transition from the S to the P pattern. However, the low percentage in Fig. 32 of DTGs when TCs are in the P/PO pattern/region

(7%) is testimony that many of the transitions fail to be completed, and when TCs do make the transition, the time spent in the P pattern is short compared to that of the S pattern.

The ECPac TCs originate in the convergent flow of the ITCZ in a similar fashion as TCs in the monsoon trough in the WPac. Although ECPac TCs may be smaller and generate weaker peripheral anticyclones, they occur frequently enough and form in a small enough area so that two TCs may occur close to one another. In 1996, TS Genevieve and Hurricane Hernan (not shown) together built a strong peripheral anticyclone to their southeast, moved northeastward, and the ITCZ then had a southwest-northeast tilt. Rather than a tilted monsoon trough changing to a completely reverse orientation as in the WPac, the zonal ITCZ of the ECPac is simply modified. This new Monsoon Trough Formation (MTF) transformation, in which two or more TCs constructively build a peripheral anticyclone and create a Poleward pattern, was observed only once in the 7-y period affected only those two TCs (Table 2). However, the essential elements of this transformation played a partial role quite often. Whether a multiple TC situation will result in a RMT involving only one TC or a MTF with two or more TCs is difficult to predict because of the nonlinear processes of building separate peripheral anticyclones that then become juxtaposed. Since the two ECPac TCs are generally smaller, the peripheral anticyclones are weaker, so that a merger of these peripheral anticyclones to form a MTF is more rare than a RTF in WPac.

Of all the TC interactions, the ITIE is the most common, and STI mode is less common. The DTI mode, which requires a small separation distance between TCs, is quite rare. Because DTI2 and DTI3 affect two TCs at a time, they occurred only twice and once,

repectively, in the 7-y sample. The count of the other indirect interaction, ITIW, is probably low because rarely are ECPac peripheral anticyclones strong enough that, when another TC to the east helps dissipate that anticyclone, there is a substantial effect on the western TC track. In other words, TCs are not in the P/PO pattern/region often enough to have their environment changed so that they make a transition back to the RP or RE regions of the S pattern.

Finally, a new TC-environment transformation known as Orography (ORO) was introduced to describe sudden track deflections toward the southern coast of Mexico in which the TC does not necessarily move along with the environmental flow. White (1995) first introduced this transitional mechanism and its physical causes. TCs that experience the ORO process are difficult to forecast and can bring extensive devastation to people and property. Forecasters must be on watch for this transitional mechanism, which occurs roughly once a year.

IV. CONCLUSION

A. FINDINGS

The Systematic Approach was developed to improve understanding of how atmospheric effects have led to the present TC position and motion, and then how these environmental effects will affect the track in the future. The first phase of the Systematic Approach requires that the forecaster examine the atmosphere, specifically the environment around a TC, and classify the scenario from a small set of environment structures (pattern/region). Classification of the ECPac TC environment structure into a limited set of eight unique synoptic pattern/region combinations described in this thesis gives the forecaster a dynamically based perspective of the current situation. Given this knowledge of what atmospheric effects are producing the recent motion of the TC, the range of possible motions in the future is narrowed.

The synoptic environment around a TC in the ECPac can be accurately described by one of four synoptic patterns (S, P, L, or M) in conjunction with certain smaller synoptic regions (RP, RE, WR, MW, PO, EF, and PF). The unique bowed shape of the STA in the ECPac requires the modification of the S pattern first introduced in the WPac by distinguishing the orientation of the trade wind easterlies steering flow with the separate S/RP and S/RE pattern/regions. The replacement of the WPac G pattern with the L pattern to describe the motion of TCs moving poleward on the eastern edge of cutoff mid-level lows was another modification required to better describe physically the cause of unusual and

difficult-to-forcast tracks. It is important that 1858 individual TC scenarios over a 7-y period could be classified in only eight synoptic pattern/region combinations. Because the tracks within each of these eight combinations are internally consistent, simply classifying the environment with this rather small list of possibilities provides a good handle on the TC motion.

One of the most difficult track forecast situations is a transitional period when the TC environment is changing. This scenario is challenging because the physical process that is acting to cause the environment change may not be readily apparent. An important objective of this Systematic Approach knowledge base is to provide the forecaster a limited, yet comprehensive, list of transitional mechanisms that explain why the environment is changing. In the ECPac, the relatively simple concept of ADV by the steering flow from one synoptic region to another region within a quasi-stationary S pattern is the third most common transitional mechanism. A more common mechanism occurs when TCs move poleward of the STA axis so that VWS, as a result of the combination of midlatitude westerlies, different winds at lower levels, or the cooler waters below, tends to decrease the TC intensity, or at least impede the poleward motion. Finally, the most common transitional mechanism is some form of the SRM process in which midlatitude waves, usually separated significantly from the TC, are able to modify the STA and hence affect the TC track.

The climatologies of the eight pattern/region combinations and transitions between them reveal the dominance of the S pattern in the ECPac. That is, TCs are classified in the S pattern 87% of the time and all recurring transitions involve TCs leaving, entering, or

changing synoptic regions in the S pattern. This dominance of the S pattern results in the seemingly simple characteristic westward TC track in the ECPac (Fig. 1). However, ECPac TCs do turn, and a forecaster equipped with the tools of the Systematic Approach can anticipate these turns.

An important aspect of ECPac TCs is that their region of formation and sustenance is "bounded" by lower SSTs to the south and north. This study emphasizes the departure from westward motion of ECPac TCs is related to digging midlatitude waves. If the trough is far enough to the northwest of a TC, then the Rossby wave dispersion effect from this digging trough often enhances the STA to the northwest of the TC via the SRM process, the flow in the S/RE pattern/region is enhanced, and the TC moves equatorward, similar to an ITIE process. If a trough is able to break the STA to the north of a TC via the SRMT process, a poleward advection into the S/WR pattern/region is induced. In this situation, the TC often dissipates because of the effects of lower SSTs and/or VWS. In either of these scenarios, the TC does not continue to exist far to the north. Because the relatively small size of ECPac TCs decreases the magnitude of Rossby wave dispersion, it is less likely than in the WPac that the RMT process will lead to a complete transition into the P/PO pattern region. The result is a collection of tracks that are quite uniform with TCs moving to the west-northwest for most of their lives.

The preceding explanation of the physical causes of the large number of straight-running TC tracks in the ECPac illustrates the most useful aspect of the Systematic Approach. Given a set of conceptual models (e.g., S/RE, P/PO, SRMT, and VWS), a

detailed environment structure or complex physical process may be presented in an accurate way in the prognostic reasoning section of a disseminated forecast product. Thus, the Systematic Approach provides the ability to communicate in a quick, standarized, and yet comprehensive manner when discussing the complex science of TC track forecasting.

B. FUTURE RESEARCH

This thesis extended and redefined the knowledge base of the ECPac track forecasting within the numerical guidance analysis phase, which is just the first step of the forecasting process (Fig. 2). Only the NOGAPS analyses have been classified to assist the forecaster in understanding the present and future environment of TC. Sometimes the NOGAPS analysis does not accurately depict the environment owing to data sparsity, etc. Different dynamical models and other track guidance may forecast the track with varying degrees of accuracy depending upon the initial environment structure or transitional mechanims that may occur during the period of the forecast. Knowing when certain models are strong or weak for different scenarios in the ECPac, which is the numerical model traits in Fig. 2, is critical to deciding what the future environment of a TC will be.

Once the forecaster is confident of the future scenario, he/she can then intelligently examine the computer output by paying close attention to objective techniques that perform well in that situation, and ignoring those that typically perform poorly. The knowledge base of objective technique traits should be developed by examining the errors associated with

each technique for TCs in each synoptic pattern/region and undergoing each transtional mechanism.

Improved objective techniques, which use the knowledge of the current environment structure and are based upon more consistent tracks, could be developed. Climatology and Persistence (CLIPER) and analog techniques, which are initiated by the forecaster after he/she has identified the current synoptic pattern/region, will most likely show improvement over techniques with no knowledge of the current synoptic situation.

The average of a collection of computer-generated objective predictions is a "safe," but unphysical, forecast. A better concept is to develop a knowledge-based expert system that can help the forecaster determine TC-environment structure and transitional mechanisms. Such an expert system organized around the Systematic Approach is being developed for the WPac, and might be extended to the ECPac. The steps followed by the forecaster require him/her to answer questions that require knowledge of the current situation. Whereas the prototype expert system uses objective criteria to suggest options, the forecaster may agree or input any other possible scenario. The true potential ability of the Systematic Approach to explain the atmosphere in a clear, comprehensive manner may eventually be exploited with an expert system that helps the tropical cyclone forecaster make optimum use of the track guidance in the ECPac, and thus improve warnings of these dangerous cyclones.

APPENDIX. ENVIRONMENT STRUCTURE SAMPLE SET

Annual summaries of the synoptic pattern/region assignments for each TC during 1990 - 1996 are provided.

1990 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	H Alma		10	1						11
2	H Boris	1.5	3			6.5				11
3	TS Cristina		10.5	2		2.5				15
4	TS Douglas	4	6							10
5	H Elida	2.5	10			0.5				13
6	TD 06E	5				3				8
7	H Fausto	4	6			2				12
8	H Genevieve	12.5					5.5			18
9	H Heman	12	6.5	2			2.5	1		24
10	H Iselle	16.5	1			1.5			2	21
11	TD 11E	3								3
01C	TS Aka		12							12
02C	TD 02C		5	1						6
12	TD 12E		6							6
13	H Julio	6.5	8.5					1		16
14	H Kenna		11.5	4	1.5					17
15	H Lowell	3.5	13.5							17
16(C)	H Marie		24	2.5		1.5				28
17	H Norbert	4	9	4.5		1.5				19
18	TD 18E	4	0.5			1.5				6
19	H Odile		11.5	4.5						16
20(C)	H Polo		2.5	3.5						6
21	TS Rachel		8.5	1	3		0.5			13
22	TS Simon	8	4							12
23	H Trudy		14	9	3	2		5		33
24	H Vance	4.5	6.5		3				5	19
1990	REGIONS	91.5	190	35	10.5	22.5	8.5	7	7	372
	%	24.6	51.1	9.4	2.8	6	2.3	1.9	1.9	100
	PATTERNS		327			22.5	8.5	14		
	%		87.9			6	2.3	3.8		
90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS		1609			135.5	58.5	55		
	%		86.6			7.3	3.1	3		

1991 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	TS Andres		2	1	5					8
2	TS Blanca		14					1		15
3	H Carlos	4	16			1.5			1.5	23
4	H Delores	6	6		1					13
5	TD 05E	4								4
6(CW)	H Enrique		9	4						13
7(C)	H Fefa	9	11							20
8	H Guillermo	4	10							14
9	TS Hilda	7				6				13
10	TD 10E	0.5		3.5						4
11	TS Ignacio		2.5				3.5			6
12	H Jimena	1.5	13	2.5			5			22
13(C)	H Kevin	7.5	14.5	13						35
14	H Linda	5	9.5	1	4.5					20
15	H Marty	9	6.5			3	3		1.5	23
16	H Nora	3	2.5	3	2		1.5			12
1991	REGIONS	60.5	116.5	28	12.5	10.5	13	1	3	245
	%	24.7	47.6	11.4	5.1	4.3	5.3	0.4	1.2	100
	PATTERNS	217.5				10.5	13	4		
	%	88.8				4.3	5.3	1.6		
90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

1992 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
01C	H Ekeka	2	9.5			1.5				13
02C	TS Hali	1.5		2.5						4
1	TS Agatha	4	0.5	4.5						9
2	TD 02E		2	2						4
3	TS Blas	1	1.5	0.5						3
4	H Celia	6.5	15	3.5						25
5	H Darby	9.5	2.5	0.5		3.5				16
6	H Estelle	3.5	5.5	3.5			4.5			17
7(C)	H Frank	6.5	10	0.5				4		21
8(C)	H Georgette	9	13						5	27
9	TS Howard	1	9							10
10	TS Isis	6	5							11
11(C)	H Javier	5.5	19.5							25
12	TD 12E	1	4.5				0.5			6
13	TS Kay	1	8							9
14	H Lester	4.5		1.5	4					10
15	TS Madeline		8							8
16	TS Newton	3	6							9
17(C)	H Orlene	2.5	14.5	5.5					1.5	24
18(C)	H Iniki (TD 18E)		10.5	1.5			5			17
19	H Paine		9			2				11
20(C)	H Roslyn	1	14.5	1.5	6	2.5		9.5		35
21	H Seymour	3.5	11	1					4.5	20
22(C)	H Tina	15.5	16.5	0.5		13	3.5			49
23	H Virgil			7	1					8
24	H Winifred	3.5		3.5	1					8
25	TS Xavier		3							3
26(C)	TS Yolanda		11.5	2.5						14
27	TS Zeke		4	2	5					11
03C	TD 03C		2	1						3
1992	REGIONS	91.5	216	45	17	22.5	13.5	13.5	11	430
	%	21.3	50.2	10.5	4	5.2	3.1	3.1	2.6	100
	PATTERNS	369.5				22.5	13.5	24.5		
	%	85.9				5.2	3.1	5.7		

90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

1993 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	H Adrian	3	9.5				4.5			17
2	TS Beatriz		0.5			3.5				4
3	TD 3E	6.5				3.5				10
4	H Calvin	9								9
5(C)	H Dora	4	9							13
6(C)	H Eugene	10.5	8.5							19
01C	H Keoni	10	7.5			2.5				20
7(C)	H Femanda	3.5	10	7.5						21
8(C)	H Greg	5	19.5	3.5						28
9	H Hilary	10.5				8			1.5	20
10	TS Irwin	3								3
11	H Jova	6	6.5	4.5						17
12	H Kenneth	5	10.5	6.5		2		1		25
13	H Lidia	6.5		1	3				1.5	12
14	TD 14E		6.5	1.5						8
15	TS Max	3.5	4.5				1			9
16	TS Norma	3.5	1.5			3				8
17	TD 17E		3	1						4
1993	REGIONS	89.5	97	25.5	3	22.5	5.5	1	3	247
	%	36.2	39.3	10.3	1.2	9.1	2.2	0.4	1.2	100
	PATTERNS	215				22.5	5.5	4		
	%	87				9.1	2.2	1.6		

90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

1994 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	TS Aletta		10							10
2	TS Bud	4.5	0.5							5
3	H Carlotta	7	8							15
4(C)	TS Daniel		13							13
5(C)	H Emilia	11.5	5.5			2				19
6(C)	TS Fabio	2	9							11
7(C)	H Gilma	8.5	11.5							20
8(C)	H Li (TD 08E)	3	20							23
9	TS Hector	5.5	0.5							6
01C	TD 01C	3.5	4	2.5						10
10(CW)	H John	22.5	11.5							34
11	H Ilena	5	2.5						1.5	9
12	TD 12E	2.5	5.5							8
13(C)	H Kristy		15							15
14(C)	H Lane	1	11.5	1.5						14
02C	TS Mele	4.5	3.5							8
15	TS Miriam		10.5	1.5						12
16	TS Norman		2				4			6
17	H Olivia		9				3		3	15
18	TS Paul		4.5				3.5	3		11
19	H Rosa				14					14
03C	TS Nona	0.5	6.5	4						11

1994	REGIONS	81.5	164	9.5	14	2	10.5	3	4.5	289
	%	28.2	56.7	3.3	4.8	0.7	3.6	1	1.6	100
	PATTERNS	269				2	10.5	7.5		
	%	93.1				0.7	3.6	2.6		

90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

1995 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	TD 01E	0.5	2.5							3
2	Adolph		5	1		6				12
3(C)	Barbara	6	15							21
4	Cosme	6	4				1			11
5	Dalila	14	0.5			3.5				18
6	Erick	3.5	2.5			2	5			13
7	Flossie	7	3.5			3.5				14
8	Gil	2	7	2		3				14
9	Henriette	5	5.5			4.5				15
10	Ismael					6				6
11	Juliette	13	3			4				20

1995	REGIONS	57	48.5	3		32.5	6			147
	%	38.8	33	2		22.1	4.1			100
	PATTERNS	108.5				32.5	6			
	%	73.8				22.1	4.1			

90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

1996 PATTERN/REGION OCCURRENCES

		S				P	L	M		
#	STORM	RP	RE	WR	MW	PO	PO	EF	PF	DTG
1	TD 01E	5.5	1.5							7
2	TD 02E		5	2						7
3	H Alma	7.5	0.5	3.5	2		1.5			15
4	H Boris	6.5	2			1.5				10
5	TS Cristina	5								5
6	TD 06E		0.5			2.5				3
7	H Douglas	5.5	10.5							16
8	TS Elida	7		8						15
9	H Fausto	5.5		2.5	2					10
10	TS Genevieve	0.5	9.5			12		1		23
11	H Hernan	2				7				9
12	TD 12E	1	5.5	1.5						8
1996	REGIONS	46	35	17.5	4	23	1.5	1		128
	%	35.9	27.3	13.7	3.1	18	1.2	0.8		100
	PATTERNS	102.5				23	1.5	1		
	%	80.1				18	1.2	0.8		
90-96	REGIONS	517.5	867	163.5	61	135.5	58.5	26.5	28.5	1858
	%	27.9	46.7	8.8	3.3	7.3	3.1	1.4	1.5	100
	PATTERNS	1609				135.5	58.5	55		
	%	86.6				7.3	3.1	3		

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